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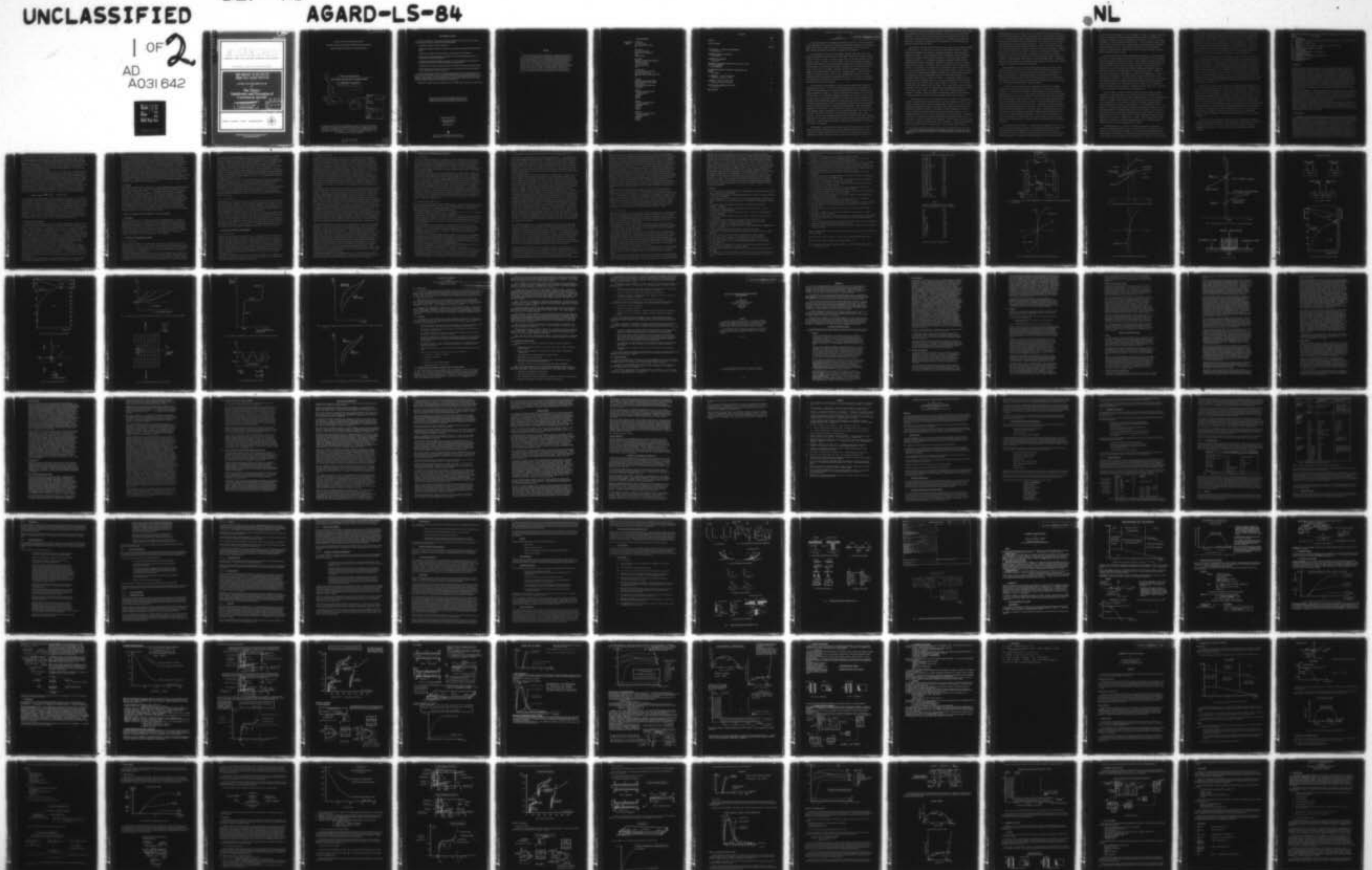

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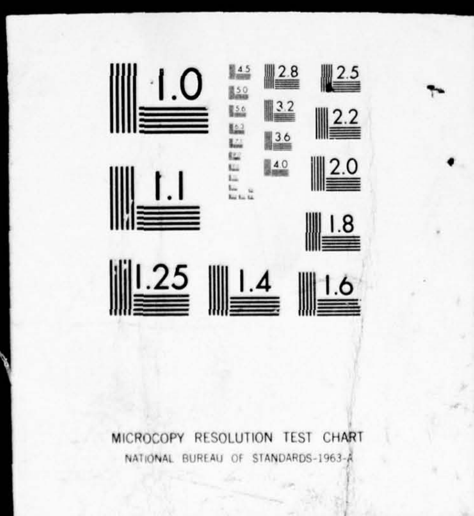

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ADVISORY GROUP FOR AEROSPACE RESEARCH & DEVELOPMENT

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on

The Theory, Significance and Prevention of Corrosion in Aircraft

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PREFACE

The true annual cost of corrosion in NATO aircraft is appallingly large, in spite of the advanced state of knowledge in this field. Interruption and reduction of service, failure of mission, hazards to personnel because of operating failures are additional important factors when assessing corrosion impact. Yet, most premature corrosion damage and failures occur for reasons already well-known, and to a major degree could be prevented by proper and timely appreciation of the problem and threat, and by the use of known preventive methods. Clearly, greater visibility of the problems, expanded engineering education and better practical transfer of technology and knowledge are needed. This Lecture Series was structured with this situation in mind. It covers the significance, implications and economics of corrosions, and the threats and preventive measures for the product life cycle: design, material selection, construction, maintenance and repair, inspection and test.

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CONTENTS

INTRODUCTION – A SURVEY OF THE PROBLEM

by

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In this brief survey of the problem of corrosion in aircraft, I shall touch only on certain highlights and the over-all situation and perspective, inasmuch as the individual papers that follow will dwell in detail on the various aspects of the total system. I trust that any unavoidable overlap with the speakers will be minimal.

It is unfortunate that the very environmental component that makes life on this planet possible also is the basis of one of man's major economic and technical problems. I refer, of course, to water - in liquid or vapor form - as the prime instigator of that universal disease, - corrosion. And since water in some form can rarely be excluded - certainly from aircraft - and since our engineering materials are basically thermodynamically unstable in our practical environment, inevitably there exists the continuing threat, at all times, of corrosion. Actually, conditions are generally worse; for example, there could be present chloride ions, dissimilar metals, or other dissimilar chemical or physical conditions, all of which could aggravate corrosion. The three approaches open to minimizing this ever-present threat lie in the design of the product (including the rare opportunity to control the environment), the selection of materials, and preventive anti-corrosion measures.

Now these points are elementary and obvious and by no means unknown to aircraft manufacturers and users. Nor have science and technology ignored the development of better basic understanding of the various phenomena associated with corrosion as well as practical measures to combat it. Indeed, our knowledge and progress in this field are both excellent. It is particularly striking, therefore, that in spite of what we know and have learned over the past few decades, and even before, we are still experiencing aircraft corrosion damage that annually is costing many, many millions of dollars, not to mention indirect penalties such as aborted missions, decreased aircraft usage factors, even at times hazards to safety of both aircraft and personnel. What is particularly regrettable - even ironical - is that much of this loss and cost could be avoided by more extensive and more intelligent use of the existing knowledge. This is not to say, of course, that there is no need for additional research and development. There certainly is such a need and hopefully these corrosion seminars will be able to pinpoint where some of this effort should be applied by defining critical problems and gaps in our knowledge. It would be well to keep this in mind during the Conference, for discussion at the end of the program.

Nevertheless, the situation does point up the fact that there does not exist an adequate transfer of technology, even a common language, among the scientist, the engineer, the designer, the practitioner and others. We should address ourselves to establishing a better mechanism for this and more effective channels of communication.

As a minimum, the designer and practitioner must be impressed with the fact that in most cases something can be done to minimize corrosion if he will only seek out the proper information. Often, the fault has been in the lack of recognition that a corrosion threat exists and that there may be a solution to it. A related fault has been poor definition of the problem, particularly poor understanding of the environmental and physical conditions that will obtain.

With respect to what corrosion is costing us, this subject will be treated at length in a later lecture. In terms of cost to cope with and minimize corrosion, I want to emphasize the importance of looking at a complete life cycle and total system when assessing cost values. Such a system must include consideration of special design and construction features, specially selected materials, corrosion-preventive measures (coatings, insulation, etc.), inspection and detection procedures, maintenance and repair measures, possible replacement of components or material, and loss of time and availability of aircraft. To a degree, cost can be shifted from one of these areas to another, but all aspects of this system must be considered in order to minimize total cost, and the optimum answer will depend on the particular situation. There is, however, an additional and complicating consideration; namely, the non-quantifiable requirement for reliability, safety, accomplishment of mission (for military aircraft), etc. - even legal liability which is tending to increase. In some cases, therefore, cost of trade-offs cannot be evaluated and, in fact, cost may be secondary or even irrelevant, although obviously every effort must be made to keep it at a minimum. Only one other related point I would make at this time; namely, that in some cases, corrosion, although undesirable, may not be harmful and therefore the most practical answer may be to allow it to proceed, within limits. For example, it may not be worthwhile, except for esthetics, to attempt to prevent entirely some superficial pitting of heavy castings in innocuous areas, provided this does not encourage slovenly habits elsewhere.

I suspect that by the end of this Conference it will be evident that aircraft are subject to practically every type of corrosion: pitting, intergranular, fatigue, stress-corrosion cracking, crevice, bacterial, embrittlement, fretting, etc.* Some of these have been more prominent and more injurious than others, depending on the application, material and prevailing conditions. For example, pitting of magnesium alloy sheet, during the period of its popularity, was very serious and costly, whereas pitting of magnesium castings, still in use, was much milder and of much less concern. Intergranular corrosion of certain high strength aluminum alloys and stainless steels was at one time a serious problem, now happily mostly remedied. Stress corrosion cracking has been and still is a major, ever-present threat, often catastrophic. The research and development on this topic continues as a major effort. The excellent scientific work in

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*The higher temperature phenomena of oxidation and sulphur attack will be dealt with at most only incidentally because high temperature attack is so important and so complex that it deserves a conference of its own and AGARD has dealt with this subject separately.

fracture mechanics has been of great value in this regard and is a good illustration of how close working between the scientist and engineer can be very effective in a practical way. In a somewhat related sense, hydrogen embrittlement, hydrogen-induced cracking and related insidious delayed failures under relatively low stresses all have long histories and continuing records of costly damage and worries. Corrosion per se as well as the corrosion preventive treatments and pre-treatments, such as electroplated coatings and prior cleaning procedures, are sometimes the original sources of this problem. Occasionally, indirect sources can be important contributors, illustrating the complexity of the problem and the need for extreme care. For example, the dry lubricant molybdenum disulphide in the presence of water vapor and friction generates hydrogen sulphide which is known to catalyze hydrogen embrittlement in very high strength steels. Fortunately, great strides have been made in understanding these phenomena and avoiding them, although unanimity of thinking still remains to be achieved.

Another important area is corrosion fatigue since fatigue is one of the major causes of failure in aircraft and, in effect, corrosion fatigue may be thought of as cyclical stress corrosion. This is one of the selected topics to be discussed in a paper at this Conference. An aggravating factor in both corrosion and fatigue is fretting, which was the subject of a special AGARD meeting in 1974. At that meeting, the interplay of fretting, corrosion and fatigue were discussed in detail from the point of view of phenomena, damage modes and remedial measures.

I shall mention only briefly one other common type of corrosion in aircraft, namely, galvanic corrosion, the formation of galvanic cells with resulting anodic corrosion. The ever-present requirement to minimize weight in aircraft and maximize performance has led to the use of a wide variety of materials, with resultant dissimilar metal contacts and strong anodic tendencies of the less noble metals such as aluminum. The Electrode Potential Tables have been of some help but are often misleading because they do not represent actual operating conditions. More practical galvanic couple tables have been prepared which are quite useful. Insulating and isolating techniques have been developed to avoid galvanic corrosion, but as in other corrosion situations, have not always been employed and, in some cases, have not been employed correctly, so that galvanic corrosion remains a wide-spread, though basically avoidable, source of trouble. It is another example of negligence in the use of existing knowledge. It should be recognized, also, that galvanic cells may be created even within a single material due to local variation in chemical, physical, metallurgical and environmental conditions.

Recognizing the above hazards, it is necessarily very important to be able to inspect for and detect incipient corrosion so as to permit prompt remedial measures that would avert more serious consequences. For critical areas that are likely to be susceptible to corrosion, original design must take into account and provide for easy access for inspection. Thereafter, the problem becomes one of detection techniques

that very often must be applied in situ; for example, in a wing. Here again, significant studies in nondestructive inspection have been made; for example, in ultrasonic and radiographic techniques, as will be discussed in a later paper. One of the more recent developments is a refined acoustic emission process. A good correlation has been found between certain corrosion reactions and high frequency, low-amplitude sounds generated during the corrosion process. This approach has been useful in detecting hidden corrosion in honeycomb panels, adhesive-bonded joints, and the assessment of corrosion inhibition against galvanic couples.

The subject of testing to assess susceptibility of materials to corrosion has been dealt with in a previous AGARD study and will be further considered in this Conference. I would merely stress at this time two points. First, although it appears obvious, one cannot over-emphasize the importance of testing under realistic conditions that relate as best possible to expected usage and exposure situations. Many failures can be attributed to the use of materials and protective schemes under operating conditions which, during testing, were either ignored or could not be anticipated. Secondly, I would inject a plea for continued emphasis on international standardization, since this is vital to the transmittal of information from one source to another and its true understanding and evaluation. This does not mean attempting to establish a few arbitrary tests often irrelevant to operating conditions as mentioned above; flexibility must certainly be maintained here. Nevertheless, there are common tests for similar and related situations, and in such cases it is important that all details that could affect results be considered and standardized to the maximum degree.

I shall not dwell on specific prevention techniques and maintenance and repair procedures, the other major topics of the corrosion system to be discussed at this Conference, but before concluding I do want to comment briefly on a topic not specifically listed in our program; namely, education, although I have touched upon one aspect of this at the beginning. I use the term "education" very broadly, starting from the university stage and proceeding through many phases to the ultimate practitioner. Too often, in the university, the student is exposed to the subject of corrosion in only an incidental, indirect or peripheral manner rather than in the sense of focussing on a major technical field, requiring the integration of many other disciplines. There are exceptions, of course, but I suspect that, in general, deliberate concentration comes rather late in the student's academic life, if at all. There continues to be a need, therefore, for creating a much larger, broadly trained corps of "corrosionologists" commensurate with the scope and magnitude of the problem.

I use "education" also in the sense of training the designer, the materials engineer, the manufacturing engineer and others who should be in the chain of activity dedicated to minimizing corrosion damage. This phase of education should never end, because improved understanding and techniques become available almost endlessly, albeit slowly at times, and new experiences and situations arise. Inherent in this latter phase

is the need for good mechanisms for technology transfer, the translation of knowledge into practical, understandable language for ready application, and the dissemination of such information through appropriate channels which may yet need to be created. Some potential routes are, of course, conferences, individual publications, handbooks and specifications. There are others and therefore this is another topic on which the Conference might well develope recommendations for international action. Though often ignored, especially in technical meetings such as this, this topic of education and communication could well be the most important of all, since technical knowledge, no matter how significant, is obviously of limited value if not communicated.

In conclusion and recapitulation, I have tried to convey in this brief summary a feeling of the immensity and scope of the problem, with some of its highlights, and yet the many opportunities for keeping it within bounds; opportunities that, unfortunately, are too often neglected. I have emphasized the importance of viewing this problem as a system, in terms of the life-cycle of the product from the early design stage through ultimate usage and maintenance. This Conference has been structured to deal with each major phase of this life-cycle and the lectures that follow will discuss in detail the topics I have only highlighted, as well as others. The system and life-cycle concept indicates the need for a planning and working team, early in the game, that would include experts in design, materials, manufacturing, inspection methods, costs, quality control and, of course, corrosion itself.

Finally, I would refer to a new facet of this subject that has developed in the last two or three years, indirectly. I refer to the general problem of shortages in the supply of certain basic materials, such as chromium. Although specific shortages will affect various countries differently, together they add up to a world problem. In the present context, shortages lead to substitution (for example, a coated material in lieu of stainless steel or paint to replace chromium) either to offset lack of availability of the original material or to reduce the increased cost resulting from limited availability. Herein lies an additional hazard from a corrosion point of view which definitely must be considered. On the other hand, intelligent substitution could be an important contribution to conservation of critically available materials and, in some cases, to the conservation of energy. Decrease in corrosion would itself be a conservation measure in terms of decreasing the needed replacement material, as well as the energy to produce it.

The lectures that follow taken in toto will provide a comprehensive coverage of aircraft corrosion and its prevention. Inevitably, gaps in our knowledge and activities will become evident and these should be kept in mind for discussion and possible recommendations for action. I wish you a productive, educational and enjoyable Conference.

CORROSION THEORY AND PRACTICE. *By W.A. Schultze, Laboratory of Metallurgy, Delft University of Technology, The Netherlands.*

Contents

1. INTRODUCTION

Most metals used in engineering practice are not stable in an aqueous environment. The metal changes from the metallic state into an oxidized state in the form of metal ions or metal (hydr)oxides; thus changing the mechanical strength of a structure in an unfavourable sense. This phenomenon, *metallic corrosion,* is the result of chemical reactions that can occur between a metal and an aqueous solution, containing different ions and/or dissolved oxygen (*electrolyte solution*). These chemical reactions involve charge transfer in the form of metal ions or electrons passing the interphase between metal and solution. They are therefore called *electrochemical reactions*, or as the solid metallic phase is usually termed an *electrode, electrode reactions.* In an electrochemical corrosion process always two or more electrode reactions are involved, from which at least one causes the oxidation of the metal, according to reactions like $Me + H_2O \rightarrow MeOH^+ + H^+ + 2e$, $Me \rightarrow Me^{z+} + ze$ or $2Me + 3H_2O \rightarrow Me_2O_3 + 6H^+ + 6e$. The oxidation reaction has to be compensated by one or more reduction reactions, such as $2H^+ + 2e \rightarrow H_2$ or $O_2 + 2H_2O + 4e \rightarrow 4OH^-$.

To study corrosion phenomena it is important to know what kind of electrode reactions could occur between metal and environment. Therefore the thermodynamical concept of the *equilibrium electrode potential* is introduced. Electrochemical reactions have a finite rate that can vary widely, so it is worthwhile to study the rate of the reactions that are involved in corrosion processes. For that reason the kinetical concepts of *polarization* and *overpotential* are treated. After that the *mixed potential theory* of electrochemical corrosion of a homogeneous metal can be introduced.

Complications arise when a metal consists of different phases or when a combination of different metals is used. These may also occur when the metal structure is exposed to an inhomogeneous environment or to stresses. In these cases localized types of attack are possible, such as, *pitting corrosion, crevice corrosion, intergranular corrosion, stress corrosion cracking* or *corrosion fatigue*. Some aspects of these corrosion forms are dealt with in this lecture.

2. CORROSION THEORY

2.1. The meaning of the concept of the equilibrium potential and its use to predict corrosion reactions

Between a metal electrode (Me) at which electrode reactions are proceeding and an electrolyte solution, there exists a difference in electric potential $\Delta\phi_{Me/sol}$. This difference in potential cannot be measured. However, differences in electric potential between two electrodes in an electrolyte solution are measurable. Such a system is called an *electrochemical cell* and the measured value, the *cell potential.* The concept of electrode potential ε of the metal Me can be introduced as the cell potential of an electrochemical cell, in which one half cell consists of the system Me/sol(II),and the other half cell of a standard hydrogen electrode (fig. 1). The latter is composed of a platinized platinum electrode in an acidic solution with an effective concentration (activity) of hydrogen ions $a_{H^+} = 1$. Hydrogen gas (H_2) with a pressure of 1 atm is bubbled along the Pt electrode. At this electrode the electrode reaction $H_2 \rightleftarrows 2H^+ + 2e$ is in equilibrium if no current passes through the half cell. The cell potential is built

up by a number of electric potential differences. Going from the right to the left in fig. 1 we find $\varepsilon = \Delta\phi_{Cu/Me} + \Delta\phi_{Me/sol(II)} + \Delta\phi_{sol(II)/sol(I)} - \Delta\phi_{Pt/sol(I)} + \Delta\phi_{Pt/Cu}$. $\Delta\phi_{Cu/Me}$ and $\Delta\phi_{Pt/Cu}$ indicate metal- metal potential differences. These are relatively unaffected by the various effects that change $\Delta\phi_{Me/sol(II)}$. $\Delta\phi_{sol(II)/sol(I)}$ is a diffusion potential between two electrolyte solutions and can be largely eliminated. $\Delta\phi_{Pt/sol(I)}$ is constant when no current flows in the half cell, so that any variation in $\Delta\phi_{Me/sol(II)}$ gives the same variation in the measured electrode potential ε. The requirement for measuring the electrode potential that no current flows through the measuring circuit, can be closely approached by using a high impedance voltmeter.

If at the metal electrode Me only one electrode reaction, e.g. $Me \rightleftarrows Me^{z+} + 2e$, is in dynamic equilibrium, the cell potential that is measured represents the equilibrium electrode potential $\varepsilon_{Me/Me^{z+}}$ of that reaction. The equilibrium potential of the standard hydrogen electrode is used as a zero reference point in a scale of electrode potentials (S(tandard) H(ydrogen) E(lectrode) scale). The sign of the electrode potential is arbitrarily chosen to be the same as the polarity observed, when the electrode in question is connected to the S.H.E.. Instead of this reference electrode, a saturated calomel electrode (S.C.E.) is often used. This electrode consists of mercury, calomel (Hg_2Cl_2) and a solution saturated with potassium chloride (KCl). The potential of this electrode, measured versus the S.H.E., is +245mV at 25°C. The electrode potential ε depends on the concentration of the reacting species in the electrolyte solution. For the equilibrium potential this dependence is given by the well known *equation of Nernst*. This equation gives for metal ion transfer reactions, $Me \rightleftarrows Me^{z+} + ze$, at a pure metal electrode (Me),

$$\varepsilon_{Me/Me^{z+}} = \varepsilon^{o}_{Me/Me^{z+}} + \frac{0,059}{z} \log a_{Me^{z+}} \quad \text{(temperature 25C)}$$

in which $\varepsilon^{o}_{Me/Me^{z+}}$ is a constant and equal to the equilibrium potential for $a_{Me^{z+}} = 1$. It is called the *standard equilibrium potential*. Similar equations can be given for electron transfer reactions, in which the reacting species are present in the electrolyte solution, both in the reduced and the oxidized state. Known ε^{o} values are arranged in the *electrochemical series of standard potentials* (see tabel 1). With these values and the concentrations, the equilibrium potentials of electrode reactions can be calculated and used to predict the behaviour of corrosion systems. This can be explained with an example, the behaviour of an iron electrode in an oxygen free, acidic ferrous solution. In this case two different electrode reactions are possible, (I) $Fe \rightleftarrows Fe^{2+} + 2e$ and (II) $H_2 \rightleftarrows 2H^+ + 2e$, with different equilibrium potentials. In such a situation the electrode reaction with the higher equilibrium potential will show a tendency to proceed in the direction of a reduction, whereas the other will do this in the direction of an oxidation; in this manner the system strives to an energetically favourable state.

2.2. The rate of corrosion reactions

The rate of a corrosion process depends on the kinetic behaviour of each electrode reaction that occurs at the corroding electrode. This can be explained using the example from the former paragraph. In case of $a_{H^+} = 1$ and $a_{Fe^{2+}} = 1$, $\varepsilon_{H_2/H^+} = 0$ V and $\varepsilon_{Fe/Fe^{2+}} = -0{,}44$ V, i.e. $\varepsilon_{H_2/H^+} > \varepsilon_{Fe/Fe^{2+}}$. If this experiment is made, the predicted behaviour can be observed. The iron electrode dissolves uniformly and hydrogen gas evolves uniformly over the whole metal surface, i.e. reaction (I) proceeds in the direction $Fe \rightarrow Fe^{2+} + 2e$, and reaction (II) in the direction $2H^+ + 2e \rightarrow H_2$. In both reactions charge is transferred, so using Faraday's law, the reaction rate can be expressed as a *current density* i. The oxidation reaction $Fe \rightarrow Fe^{2+} + 2e$, donating electrons to the iron electrode, is called an *anodic* reaction, and the reaction rate is given by the *anodic current density* i_a (by definition positive). The reduction reaction $2H^+ + 2e \rightarrow H_2$, accepting electrons from the iron electrode, is called a *cathodic* reaction, and the reaction rate is given by the *cathodic current density* i_c (by definition negative).

The reaction rate i of an electrode reaction is finite. It depends on $\Delta\phi_{Me/sol}$, and is therefore a function of the electrode potential ε of the electrode at which the reaction proceeds. The phenomenon that ε deviates from the equilibrium potential ε_{eq}, if an electrode reaction proceeds in the anodic or cathodic direction, is defined as *anodic* or *cathodic polarization*. The difference between ε, at a certain i_a or i_c, and ε_{eq} is measured as *overvoltage* and indicated by $\eta = \varepsilon - \varepsilon_{eq}$. The relation between i and ε or between i and η can be given graphically for a certain electrode reaction in the form of a polarization curve (see fig. 2).

In the experiment the iron electrode must have the same electrode potential over the entire surface in the well conducting homogeneous environment. This means that at some *mixed potential* between the

equilibrium potentials of reactions I and II, the reaction rates of both reactions are equal, i.e. $i_a = -i_c$, as is schematically indicated in fig. 3. For the overall corrosion reaction a polarization curve can be constructed by adding algebraically the polarization curves of the separated reactions. Several factors may determine the shape of the polarization curve of a reaction. For corrosion processes two of these factors are important. The first one is a charge transfer overvoltage, which occurs when the reaction rate is controlled by charge transfer at the interface metal/solution. In this case polarization curves are obtained with a shape, as given in fig. 2. A second possibility is a diffusion overvoltage when the reaction rate is controlled by the diffusion rate of the reacting species from the electrolyte solution to the electrode surface. In an acidic environment the corrosion process is usually controlled by charge transfer polarization of the reaction $2H^+ + 2e \rightarrow H_2$. In neutral or alkaline solutions the corrosion rate is often determined by the rate of the cathodic reaction $O_2 + 2H_2O + 4e \rightarrow 4OH^-$. At high overvoltages the diffusion rate of O_2 to the electrode limits the reaction rate to a limiting current density i_L, independent from ε (see fig. 4). In this case all environmental changes that increase the diffusion rate of O_2 will increase the corrosion rate.

2.3. Passivity

With a number of important metals and alloys used for structural engineering purposes an anodic oxidation reaction of the type $2\ Me + 3H_2O \rightarrow Me_2O_3 + 6H^+ + 6e$ can proceed under suitable circumstances. If this reaction leads to the formation of an oxide film on the metal surface that acts as a closed barrier layer, the metal is shielded from its environment. The metal oxide can be relatively stable over a considerable range of electrode potentials, even in certain aggressive environments. If the slowly dissolving barrier is constantly renewed by the formation of new oxide, due to an appropriate cathodic reaction, the corrosion rate will be low compared to the non-oxidized active state and the metal is said to be *passive*. This behaviour is shown by the polarization curves in fig. 5. Initially the metal goes actively into solution according to $Me \rightarrow Me^{z+} + ze$ under the driving force of the simultaneously occurring cathodic reaction. Before a mixed potential at the active electrode is reached, the oxide forming reaction starts and the electrode is covered with oxide. Now the corrosion rate is given by i_{pass}, the current density required to renew the slowly dissolving oxide layer. Passivity can be observed with metals like Fe, Ni, Cr, Al, Ti and a number of their alloys.

3. FORMS OF LOCAL CORROSION CAUSED BY INHOMOGENEITIES IN METAL OR ENVIRONMENT

3.1. Introduction

Until now both the metal and its environment were considered as homogeneous phases in which case a uniform attack of the metal by the corrosion process can be expected. However, engineering metals have seldom a homogeneous structure and during practical use local differences in the composition of the environment, in the temperature or in the mechanical stress situation may occur. These heterogeneities can cause dangerous forms of localized attack, such as pitting corrosion, crevice corrosion, galvanic corrosion, intercrystalline corrosion, stress corrosion cracking and corrosion fatigue. It is imposible to treat all the aspects of these forms of corrosion in a short lecture. After a short general introduction to each type, one or two illustrative cases will be discussed.

3.2. The effects of an inhomogeneous environment

3.2.1. *Pitting corrosion.*

Pitting corrosion is a form of localized attack that results in holes in the metal with little or no general dissolution of the rest of the metal surface. Most metals used in a passive condition, such as Al, Al-alloys, Fe-Cr, and Fe-Cr-Ni-alloys, are sensitive to pitting corrosion, especially in environments, containing chloride ions. The propagation of a pit is caused by a large difference in the composition of the environments, in- and outside the pit.

Pitting can be demonstrated with pure aluminium. Even in this rather homogeneous metal, pitting can occur in a neutral aerated chloride solution. The initiation process by which the pits develop has not been definitely clarified. Recent work by Foroulis and Thubrikar [1] indicates that pit nucleation is caused by the adsorption of chloride ions under the influence of the electric field, followed by the formation

of soluble basic aluminium hydroxychlorides. This process will have a high probability of repeating itself at the same site since at a constant electrode potential the electric field will tend to be stronger at the point where the oxide film is thinned by the dissolution process. The penetration of the oxide layer is followed by an anodic reaction, $Al + H_2O \rightarrow AlOH^{2+} + H^+ + 3e$, while the cathodic reaction, $O_2 + 2H_2O + 4e \rightarrow 4OH^-$, occurs on parts of the adjacent aluminium oxide surface. This causes an acidification of the solution at the iniation spot, but also a local surplus of positive ions. Negative ions, among which chloride ions, will migrate to this spot to restore electroneutrality in the pit nucleus. This leads to a large difference in composition of the electrolyte solution in the pit nucleus compared to that of the bulk solution, such that repassivation of the attacked area becomes impossible. The result is a continuously growing pit that contains an electrolyte solution with a high concentration of $AlCl_3$ and a low pH, even if the bulk solution is neutral [2]. In the pit hydrogen gas is produced by the cathodic reaction $2H^+ + 2e \rightarrow H_2$.

The pitting process of Al, and also of other passive metals and alloys, only starts if the electrode potential is more positive than a critical value, the *pitting potential* ε_p. The pitting potential can be determined by electrochemical methods. In these methods the test specimen is made part of an electrochemical cell and the electrode potential can be varied with an impressed current. At $\varepsilon > \varepsilon_p$ pitting starts, which is indicated by a sudden increase in current density. It is generally accepted that there exists for pitting sensitive metals a second electrode potential, the *protecting potential* $\varepsilon_{pp} < \varepsilon_p$, below which the propagation of already existing pits comes to a stop. Recently Broli and Holtan [3] investigated thoroughly the different ways of measuring ε_p and ε_{pp} and reached the conclusion that for Al, $\varepsilon_p = \varepsilon_{pp}$.

3.2.2. *Crevice corrosion.*

Crevice corrosion is a form of local attack, which can be observed within crevices or other shielded areas of metal surfaces, exposed to a corrosive environment, in which the metal is normally in a passive condition. The process is triggered by a local difference in composition of the environment. It can be illustrated by the behaviour of passive alloys in a medium with oxygen as the passivating agent. The slowly dissolving protective oxide layer is restored by the reaction (I) $2Me + 3H_2O \rightarrow Me_2O_3 + 6H^+ + 6e$, which is compensated by the cathodic reaction (II) $O_2 + 2H_2O + 4e \rightarrow 4OH^-$.

If the metal structure contains narrow, liquid filled, crevices (e.g. between metal and gaskets), where the supply of oxygen is restricted, the oxygen content in the crevice will be depleted due to reaction II. This causes an acidification of the liquid in the crevice, and also a migration of Cl^--ions into the crevice to restore electroneutrality. The result of both effects is a destruction of the passive layer in parts of the crevice. The metal at the active spots is then dissolving at a high rate, according to the reaction $Me + H_2O \rightarrow MeOH^+ + H^+ + e$, with the compensating oxygen reduction taking place on the much larger adjacent area outside the crevice (see fig. 6). If often takes a long incubation time to reach this unstable situation, which shows much resemblance with the conditions for pitting corrosion.

3.3. The effects of difference in alloy composition

3.3.1. *Galvanic corrosion.*

Different metals may be present in the same construction. If these metals are in direct contact with each other, and the construction is exposed to a corrosive environment, the corrosion rates may be different from those of the single metals in the same environment. The metal with the lowest corrosion potential, when exposed separately, will show an increased corrosion rate, when it is connected to a metal with a more positive corrosion potential. The latter metal will have a decreased corrosion rate. The anodic reaction dominates on the part of the combination with the increased corrosion rate *(anodic area)*, the cathodic reaction dominates on the part with the decreased corrosion rate *(cathodic area)* (see fig. 7). Corrosion potentials of engineering metals and the behaviour of metal combinations in a number of environments have been determined and published to facilitate the choice of acceptable combinations [4, 5, 6, 7].

In a system which shows galvanic corrosion, the ratio of anodic to cathodic area is of importance. If a combination has to be used with a large difference in the corrosion potentials of the separate parts, the cathodic area should be small compared to the anodic area.

3.3.2. *Intergranular corrosion.*

In a homogeneous polycrystalline metal, crystals of different orientation are separated by grain boundaries. In these transition regions the atomic packing is more imperfect than in the matrix. In a corrosive environment these regions can be preferentially attacked in comparison with the adjacent crystal faces. The difference in reactivity is usually so small that macroscopically a uniform attack is observed. There can however be large differences in reactivity, if along the grain boundaries zones are formed with a composition, different from the matrix. A number of engineering alloys shows this metallurgical state, under certain conditions of composition and heat treatment. In a corrosive medium this may lead to a severe local attack of the grain boundary regions with relatively little corrosion of the matrix, causing a desintegration of the alloy, which is called intergranular corrosion.
Some of the middle and high strength Al alloys can be quite susceptible to this intergranular attack, especially in aqueous environments containing chloride ions and dissolved oxygen. In these alloys this type of corrosion is caused by differences in corrosion potential or pitting potential of the various constituents and zones along the grain boundaries and the matrix. As examples the behaviour of two binary alloys will be treated, one with Mg, the other with Cu. Both alloys have in common that the alloying element is more soluble in the Al matrix at high temperatures than at room temperatures (see fig. 8 and 9).
The strengthening effects of Mg, due to the relative large size of the Mg atoms, compared to the Al atoms, increases with Mg content. This has led to the use of supersaturated alloys. These will however show a tendency to transform to the equilibrium, consisting of a solid solution of Mg in Al (α phase) and the intermetallic compound Mg_2Al_3 (β phase). The nucleation rate for this second phase is rather slow. Only when the Mg content exceeds 3,5 w/o, appreciable amounts of Mg_2Al_3 may precipitate on the long run. Corrosion rates, for example in a neutral aerated NaCl solution, are different for the α phase and the Mg_2Al_3 precipitate. The corrosion potential (mostly approximately the pitting potential) of some alloying metals, of solid solutions of these metals in Al, and of intermetallic compounds formed by them, measured in an aqueous solution, containing 53g/l NaCl, 3g/l H_2O_2 at 25C, are given in table 2 [8, 9, 10]. From these figures follows that Mg_2Al_3, present in an α phase, will corrode preferently in such an environment. If the Mg_2Al_3 is precipitated continuously along the grain boundaries, the alloy will be susceptible to intergranular corrosion, This is confirmed by the good correlation which is found between the microstructures of Al-Mg alloys and their resistance to intergranular corrosion. An alloy in which Mg is retained in a supersaturated condition shows no intergranular corrosion. A heat treatment that facilitates the diffusion of Mg atoms, leads to an accelerated formation of a continuous grain boundary precipitate, resulting in an alloy that is highly susceptible to intergranular corrosion. At still higher temperatures the diffusion of Mg is so fast that the Mg_2Al_3 precipitate, striving to reach its physical equilibrium shape, will form separate globular particles and the alloy is again resistant to intergranular corrosion.

Solution treated and quenched Al-Cu alloys are, just as the Al-Mg alloys, stronger than pure Al at room temperature. In contrast with the Al-Mg alloys this strengthening effect is caused by the formation of very small Cu-rich zones that are coherent with the matrix (Guinier-Preston zones) and semi-coherent precipitates (θ'-phase). These can be considered as intermediate stages in the formation of the equilibrium precipitate $CuAl_2$, the θ-phase (see fig. 9). Artificially ageing by heating the metal in the 150-200C range, stimulates the precipitation of intermediate phases in the grain bodies and improves therewith the strength, but also causes precipitation of $CuAl_2$ in the grain boundaries. If increasing amounts of boundary precipitate are formed, regions depleted in Cu, will develop along the grain boundaries. Table 2 shows that these depleted zones have a more negative corrosion potential than the Cu containing solid solution of the grain body and the $CuAl_2$ phase. The depleted zones will corrode preferentially in a corrosive medium such as an aerated sodium chloride solution, and intergranular corrosion will be possible if they form a continuous system along the grain boundaries. As the precipitation behaviour is influenced by the Cu content, rate of quench after solution treatment, plastic deformation after quenching, and ageing treatment, it will be clear that these factors will also affect the susceptibility to intergranular corrosion.
The precipitation phenomena in the high strength Al alloys, i.e. the ternary Al-Zn-Mg alloys and the quaternary Al-Zn-Mg-Cu alloys are more complicated but intergranular corrosion processes in these alloys can also be understood by accepting the existence of active paths along the grain boundaries.

3.4. The effects of an inhomogeneous stress distribution

3.4.1. *Introduction.*

If a part of an engineering construction is stressed in a corrosive environment two special types of failure may occur. The first type is due to a conjoint action of a static tensile stress in the metal, and a corrosive medium. Both influences separately being harmless, the combination can result in a dangerous form of cracking. This phenomenon which, wholly or partly, is caused by electrochemical reactions, is called stress corrosion cracking (s.c.c.). The second type, due to the combined action of a cyclic stress and an aggressive environment, also leads to premature failure of metals. This phenomenon is called corrosion fatigue.

The distribution of stress can be a third form of heterogeneity in a corroding system, in addition to the already discussed inhomogeneities in the environment and the metal. Once a crack is initiated, the nominal stress in unequally distributed and high stress concentrations at the tip of the propagating crack occur. The theory of linear elastic fracture mechanics gives the stress distribution around the crack [11]. Directly in front of the crack tip the situation is dominated by the stress in the y-direction (see fig. 10) and given by $\sigma_y = \frac{K_I}{\sqrt{2\pi x}}$, where K_I = stress intensity factor (the subscript I denotes that the opening mode is perpendicular to the crack faces). The value of K_I depends on the crack length l, the nominal stress S and the geometry of the cracking part, in the following way: $K_I = S\sqrt{l}.f$ (geometry). Very close to the crack tip, σ_y exceeds the yield strength and a small plastically deformed area will be formed. When K_I reaches a critical value, more strain energy is released, during a small extension, than is necessary to create new crack surfaces and a new plastically deformed zone. The critical value for K_I has a maximum value for a thin plate with a plane stress situation and a relatively large plastic zone in front of the crack. For a thick plate with a plane situation and a relatively small plastic zone, K_I reaches a minimum value, indicated by K_{IC}.

3.4.2. *Stress corrosion cracking (s.c.c.).*

Quite a lot of research work has been done over the past 40 years, to find an explanation for this insidious form of corrosion with the purpose of coming to a more predictable behaviour of structural engineering metals. This has not yet led to a complete understanding of the mechanism(s). Any succesful working hypothesis should explain the following phenomenological aspects:

- Pure metals are generally not susceptible to s.c.c.. The susceptibility to s.c.c. of alloys is affected by the chemical composition and the distribution of precipitates.
- Generally there is a limited number of environments in which a given alloy will show s.c.c.. Alloys of high inherent corrosion resistance due to a passive condition e.g., 18/8 stainless steels and Al-alloys, require an aggressive ion for s.c.c. such as Cl^-. Alloys of low inherent corrosion resistance e.g., mild steels or Mg-base alloys, require an environment which has a tendency to passivate, i.e. contains NO_3^- or CrO_4^{2-} ions.
- S.c. cracks proceed in a direction perpendicular to the direction of the tensile stress (applied externally or present as internal stress due to pretreatment of the metal). Both intergranular and transgranular s.c, cracks are observed. Intergranular cracking proceeds like intergranular corrosion along grain boundaries but is confined to a few cracks. Transgranular cracking advances without preference for grain boundaries.
- S.c. failure of a structural part proceeds through three stages, initiation of the crack, propagation of the crack and the final cracking failure due to overload. The initiation period varies from a few seconds to many days. For high strength Al alloys propagation rates are observed between 10^{-11} m/s ($\sim 3.10^{-4}$ m/y) to 10^{-4} m/s, depending on alloy type, temperature, environment and stress situation [12].
- The susceptibility for s.c.c. increases with increasing temperature.
- A shift of the electrode potential to values more negative than the corrosion potential, by external means (cathodic polarization), has a favourable effect on the sensitivity to s.c.c.
- An increase in the nominal stress (and therewith an increase of the stress intensity factor K_I) decreases the time to failure. In environments in which the alloy is susceptible to s.c.c., crack growth can be observed at K-values lower than K_{IC}. Under such circumstances the value of K_I increases with increasing crack length until the K_{IC} value is reached and unstable fracturing starts. An arbitrary K_I-value can be defined below which crack growth due to stress corrosion effects is so slow that K_{IC}

is only reached after many years. Such a threshold value is called the $K_{I\,SCC}$-value (fig. 11).

Several theories have been proposed to explain the different phenomena of s.c.c.. Some of them deal with initiation and propagation while others only deal with propagation, initiation being caused by other effects, such as pitting or intergranular corrosion. All these theories contain elements of speculation and no one is accepted without doubt. It is convenient to rationalize the problem in terms of different mechanisms applicable to different types of alloys. These mechanisms are based on two different ideas. The main point in the first idea is that a weakening of the metal bond in the metal lattice is caused by adsorption or absorption of certain species, which are either present in the environment or formed by electrode reactions. The second idea is that a fast local electrochemical attack has an important function in the destruction process.
To the first group belongs the so called stress sorption cracking theory [13]. This theory tries to give a unifying mechanism for the cracking of stressed solids in a liquid environment. Analogous to the cracking of plastics in certain organic liquids and the cracking of metals in specific liquid metals, s.c.c. in aqueous solution is explained by the effect that specific adsorbates can have on the strength between the metal atoms at the extreme root of a notch or a crack tip, subjected to a high tensile stress. This can be explained with the aid of fig. 12, which shows a metal under a sustained load, with a crack initiated by a notch or otherwise. Normally the metal will show plastic deformation if a critical shear stress τ_{cr} is exceeded. If however the bond strength between the metal atoms at the crack root is decreased by adsorbates, it is possible that a critical value of the cleavage stress σ_{cr} is exceeded prior to τ_{cr}, and a brittle fracture, perpendicular to the loading direction, will take place. The effects of temperature, cathodic polarization and certain inhibiting anions can be explained by speculating on the influence these factors would have on the adsorption of the damaging species. Still more speculative considerations are needed to explain the effects of alloy structure and stress on the adsorption process. The theory of hydrogen-assisted stress corrosion [14] belongs also to the first group. The idea is that hydrogen atoms formed by the cathodic reduction of H^+ or H_2O are partly absorbed and then diffuse into the metal under influence of a concentration and a stress gradient. The maximum hydrogen concentration will occur at the plastice-elastic interface in front of the crack where the hydrostatic stress reaches a maximum. There it causes decohesion effects, expecially at grain boundaries and at second phase particles [15]. These effects can also occur in aerated neutral or alkaline solutions. Though in these solutions the reduction rate of H^+, and generally also of H_2O, is slow, the electrolyte solution in the crack is acidified due to the predominant anodic reaction in the crack, $Me + H_2O \rightarrow MeOH^+ + H^+ + 2e$, and the reduction of hydrogen ions can taken place at the crack walls. In general this mechanism of hydrogen-assisted s.c.c. fits well for the behaviour of metals with a body centered cubic structure because these are liable to hydrogen embrittlement. Others extend this mechanism also to metals with a face centered cubic structure [16, 17, 18, 19].

The electrochemical theories of s.c.c. are based on the presence of active paths in the metal, along which the cracks propagate owing to a fast anodic dissolution process (active path corrosion). These active paths are either present in the alloys in the form of intercrystalline zones of a different composition than the matrix (pre-existing active paths), or in the form of strain generated active paths. An example of cracking associated with strain generated active paths is, where cracking of a protecting surface layer, e.g. an oxide layer, due to the formation of slip steps in the underlaying metal, exposes bare metal which reacts with the environment. If dissolution in lateral directions is restricted [20] this process can result in cracking. The necessary restricted lateral dissolution can be caused by a repassivation of the crack walls, leaving a very small active area at the crack tip. This is combined with the effect that dislocations emerging at the crack tip of the straining metal, stimulate the anodic dissolution process so that high current densities may be sustained at the crack tip [21].

A number of the medium and high Al alloys, used in aeronautical industry, are sensitive to s.c.c.. For the development of more resistant alloys it is important to know which mechanism causes the stress corrosion phenomena in these alloys. Since the crack path is essentially intergranular the s.c.c. of Al alloys could be considered as a special case of intergranular corrosion. The cracking is then associated with the presence of pre-existing paths in the alloy in the form of continuous grain boundary precipitates or depleted zones that are anodic to the matrix [22] (see also 3.3.2). This process which is

possibly valid for alloys of the Al-Mg and Al-Cu type, could be called stress assisted intergranular corrosion. For alloys of the Al-Zn-Mg type, and other more complicated high strength alloys, this pattern of behaviour is generally not accepted, as they are found to be susceptible to s.c.c. in environments in which they are not susceptible to intergranular corrosion without stress. In that case it is necessary to explain crack initiation and growth in the absence of a pre-existing susceptible path. Sprowls and Brown [23] and Speidel [12, 24] give an extensive survey of proposed mechanisms for the cracking of these alloys from which can be concluded that it is still a controversial subject, both with regard to the experimental results, and to the interpretation of these results. A survey of more recent publications does not show an improvement in this situation [9, 10, 25-32]. The theories are generally based on the strain generated active path model. The active path is generated by slip bands emerging at the grain boundaries. One of the assumptions is that slip takes place in precipitation free zones along the grain boundaries, followed by a preferential corrosive attack. In that case the presence and the width of these precipitation free zones can be of importance. Another suggestion is that slip occurs across the whole grains in which case quantity and form of precipitates in the grain are of influence on the s.c. susceptibility. Also the combined mechanism of a rapid dissolution of discontinuous anodic precipitates in the grain boundaries, like $MgZn_2$ followed by a tearing of the bridges between these precipitates, is brought forward. Others advocate the decohesive effects of hydrogen, developed in the cracks [16, 17, 18, 19].

Although the theoretical understanding of the influence of the structure of Al alloys on the s.c. susceptibility is still limited, there is much empirical experience. If the crack velocity v of a propagating crack is studied as a function of the stress intensity factor K_I, generally a graph as given in fig. 13 is obtained [33]. This simplified v-K diagram shows a stress dependent part (region I) at low K-values, a stress independent part (region II) at intermediate stress intensities and another stress dependent part (region III) at high stresses. Region I and II are typical for commercial alloys. The s.c. susceptibility can be improved in two ways, by shifting region I to the right and region II to lower crack rates. In this way the aluminium industry has developed high strength alloys with a superior resistance to s.c.c.. Especially for the Al-Zn-Mg-Cu system, the crack growth rates of the velocity plateau (region II) could be favourably effected by alloy composition and heat treatment.

3.4.3. *Corrosion fatigue.*

Metals can fail by fatigue in an inert environment, if they are subjected to cyclic stresses much lower then their static fracture strength. In most nonferrous alloys, for example, Al alloys, the allowable cyclic stress always decreases as the required number of load cycles increases. In ferrous alloys an *endurance limit* is reached below which the metal can be cycled for an indefinite number of times without failing. Corrosion fatigue is the combined action of a corrosive environment and a cyclic stress. It leads to an appreciable reduction in fatigue life.

The fatigue process starts with a crack initiation period (stage 1) which is followed by a period of visible propagation of the crack (stage 2). There is no general agreement how both periods are divided over the total fatigue life. One of the problems is that the length of the initiation period depends on the sensitivity of the crack observation method.

In an inert environment the crack initiation starts with the formation of cyclic slip bands at the surface, gradually developing into intrusions and extrusions at which a microcrack along a slip plane or a grain boundary is formed. This initiation process is accelerated by corrosion reactions. The exact mechanism of the environmental action still remains elusive. In general four principal effects are considered, pitting corrosion, preferential solution of anodic areas induced by deformation, protective film destruction, and surface energy reduction by adsorption of species present in the environment [34]. According to investigations of Duquette and Uhlig [35] the initiation process is only accelerated if the general corrosion rate of the metal exceeds a critical value.

Stage 2 of the fatigue process is also shortened if the cyclic loading takes place in a corrosive medium. There are a number of different hypotheses on fatigue crack growth [36-39], but at the moment nothing conclusive can be said about the fundamental aspects of the environmental effects on this growth process.

For aircraft structures the principle of fail-safe design is often used. This is based on the idea that structural metals may contain natural defects, such as, inclusions, weld cracks, and corrosion pits, that may act as starting points for fatigue cracks. In that case the fatigue life is controlled by the crack

propagation rate and a precise knowledge of this value is required. Such figures are obtained by experimental work in which the fatigue crack growth process is studied for a given material, environment, load range, wave form of the load cycle, and cycling frequency. Crack propagation rates are generally correlated with the stress intensity factor, to obtain comparable figures for specimens of a different shape (limitations in the use of this parameter are given by Schijve [40]). In fatigue tests a stress cycle is characterized by two nominal stress values, S_{max} and S_{min}. This implies that the stress at the propagating tip can be specified by two values, K_{max} and K_{min} (see fig. 14). The test results are usually given as fatigue crack growth rate per cycle $\frac{dl}{dn}$ as a function of K_{max} and K_{min}, or as $\frac{dl}{dn} = f_R\ (\Delta K)$, in which $\Delta K = K_{max} - K_{min}$ and f_R depends on the stress ratio $R = K_{min}/K_{max}$. The effect of a corrosive environment on the growth rate of a fatigue crack can be evaluated utilizing $\frac{dl}{dn}$ versus ΔK plots, measured at the same R, frequency, wave form, and temperature as is shown schematically in fig. 15. The environmental effects increase with increasing temperature and also depend on the frequency as, again schematically, is shown in fig. 16. The wave form of the load cycle also seems to exert influence on the fatigue crack growth, in a sense that the corrosive effects are mainly operative in the ascending part of the load cycle [41]. All these effects suggest that time and temperature dependent processes, such as diffusion controlled electrode reactions, or adsorption or adsorption processes, are effective in fatigue crack propagation.

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TABLE 1

Electrochemical Series of Standard Potentials (25C)

	V
$Mg \rightleftarrows Mg^{2+} + 2e$	- 2.37
$Al \rightleftarrows Al^{3+} + 3e$	- 1.66
$Ti \rightleftarrows Ti^{2+} + 2e$	- 1.63
$Mn \rightleftarrows Mn^{2+} + 2e$	- 1.18
$H_2 + 2OH^- \rightleftarrows 2H_2O + 2e$	- 0.83
$Zn \rightleftarrows Zn^{2+} + 2e$	- 0.76
$Cr \rightleftarrows Cr^{3+} + 3e$	- 0.74
$Cr^{2+} \rightleftarrows Cr^{3+} + e$	- 0.56
$Fe \rightleftarrows Fe^{2+} + 2e$	- 0.44
$Cd \rightleftarrows Cd^{2+} + 2e$	- 0.40
$Co \rightleftarrows Co^{2+} + 2e$	- 0.28
$Ni \rightleftarrows Ni^{2+} + 2e$	- 0.25
$Sn \rightleftarrows Sn^{2+} + 2e$	- 0.14
$Pb \rightleftarrows Pb^{2+} + 2e$	- 0.13
$H_2 \rightleftarrows 2H^+ + 2e$	0
$Cu \rightleftarrows Cu^{2+} + 2e$	+ 0.34
$4OH^- \rightleftarrows O_2 + 2H_2O + 4e$	+ 0.40
$Fe^{2+} \rightleftarrows Fe^{3+} + e$	+ 0.77
$Ag \rightleftarrows Ag^+ + e$	+ 0.80
$Pt \rightleftarrows Pt^{2+} + 2e$	+ 1.2
$2H_2O \rightleftarrows O_2 + 4H^+ + 4e$	+ 1.23

TABLE 2

Corrosion (pitting) potentials of Al, Al alloys, their alloying elements and intermetallic phases [8]

Phase	V(SHE)
Mg	- 1.39
Zn	- 0.74
Mg_2Al_3	- 0.90
Al + 4Zn	- 0.71
$MgZn_2$	- 0.71
Al + 1Zn	- 0.62
Al + 7Mg	- 0.55
Al + 5Mg	- 0.54
Al + 3Mg	- 0.53
Al 99.95	- 0.51
Al + 2Cu	- 0.41
$CuAl_2$	- 0.39
Al + 4Cu	- 0.35
Cu	+ 0.14

Solution: 53 g/l NaCl, 3 g/l H_2O_2 at 25C.

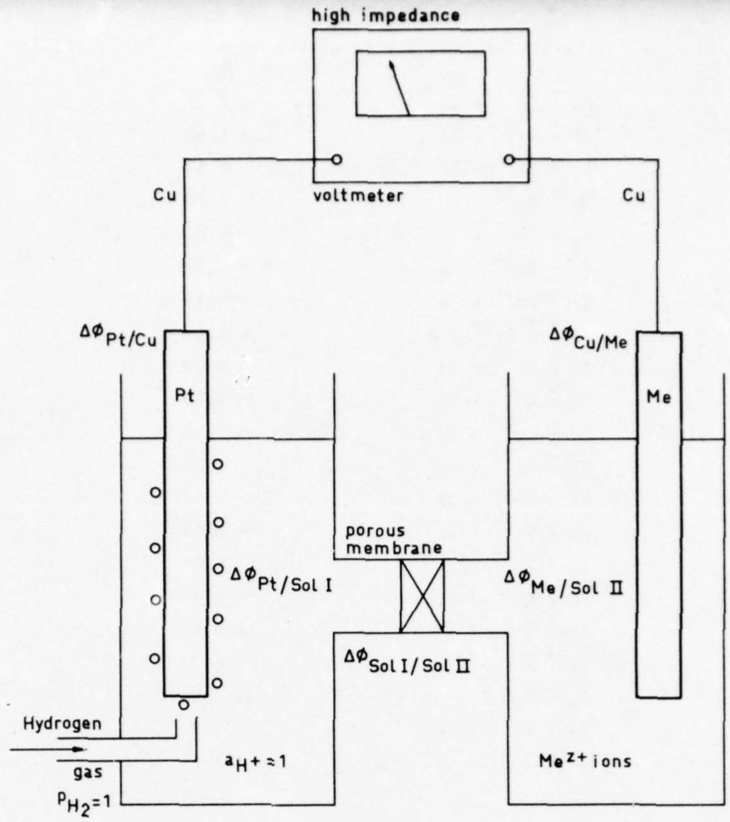

Fig. 1. Electrochemical cell, $Cu/Pt/H_2/H^+//Me^{z+}/Me/Cu$, for the measurement of the electrode potential of a metal Me.

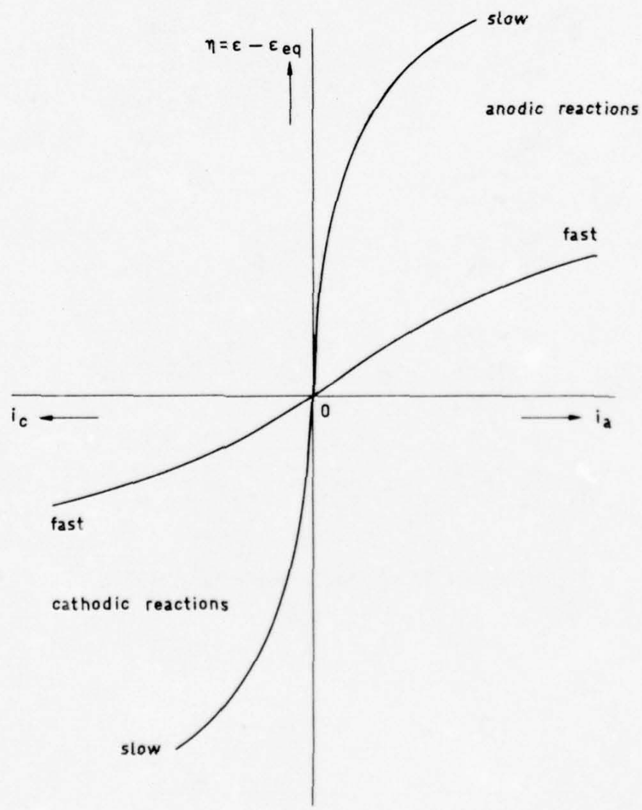

Fig. 2. Polarization curves for slow and fast electrode reactions.

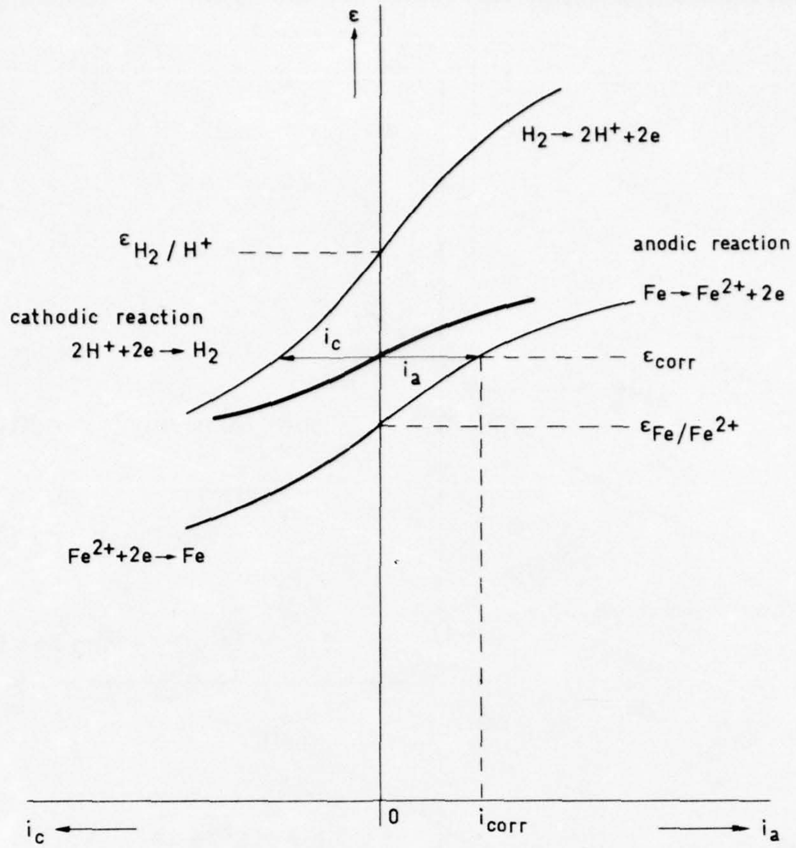

Fig. 3. Schematic polarization curves for the corrosion system iron/acid.

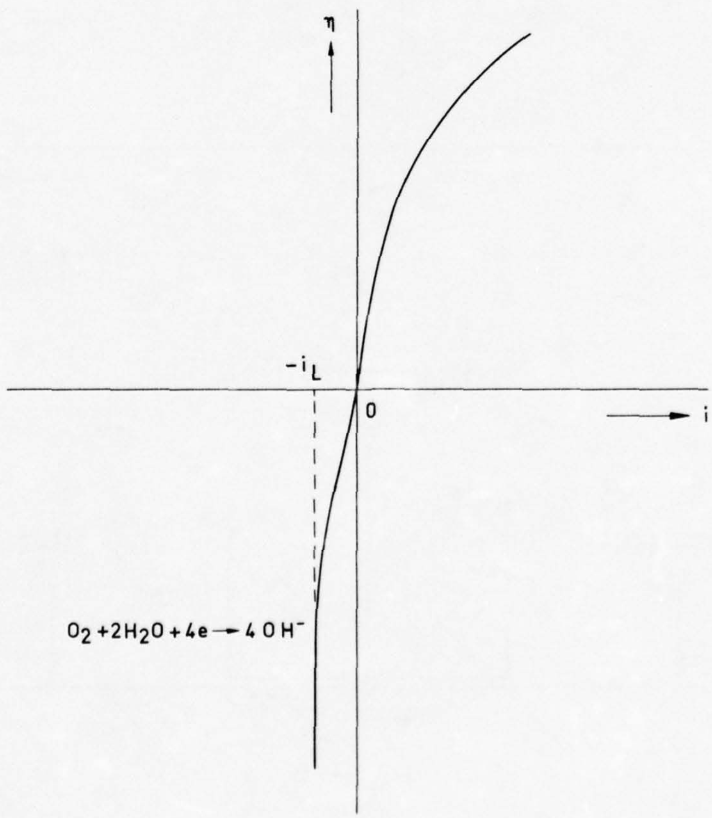

Fig. 4. Diffusion limited cathodic reduction of oxygen.

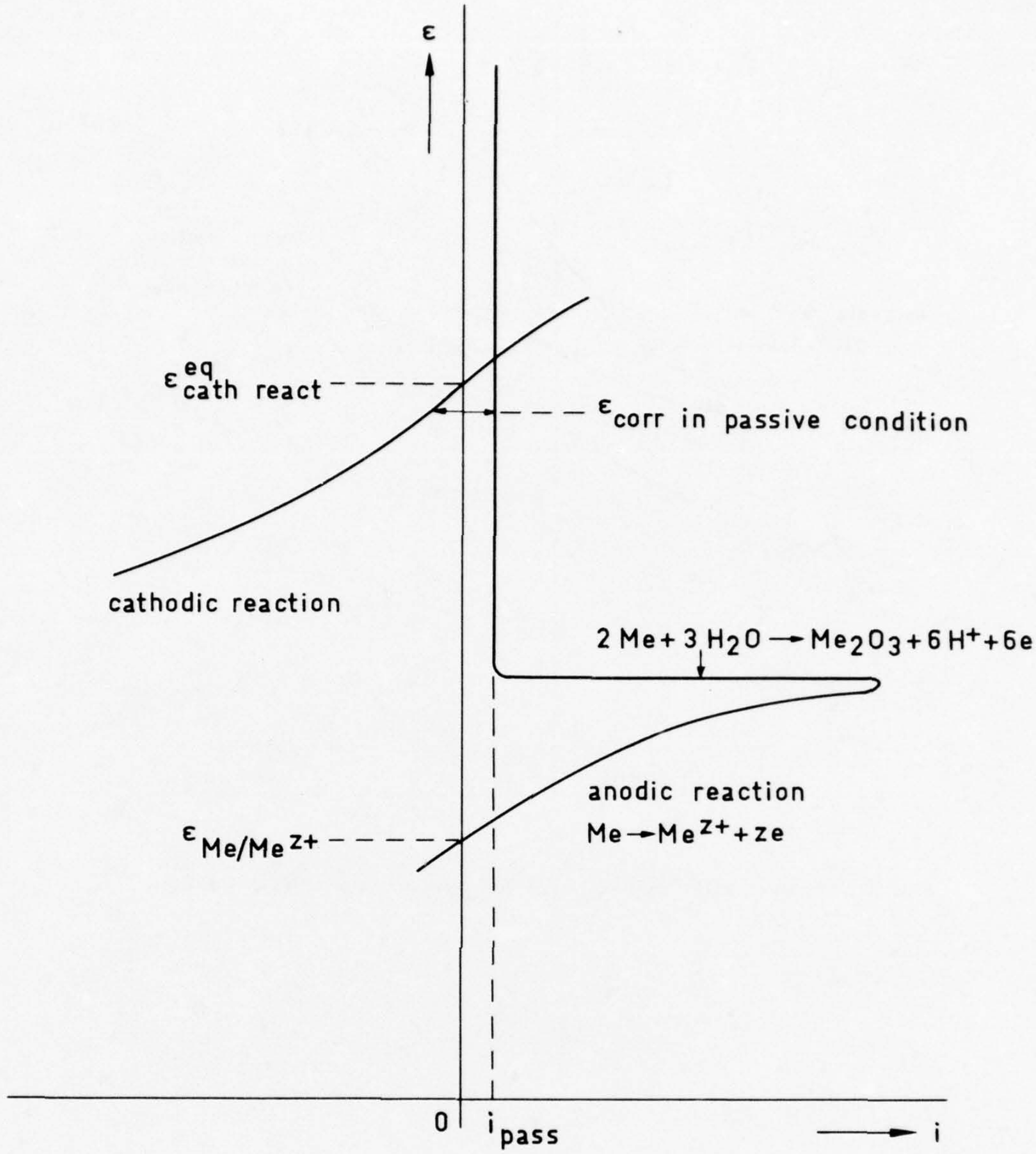

Fig. 5. Anodic polarization curve for a metal in a passivating environment.

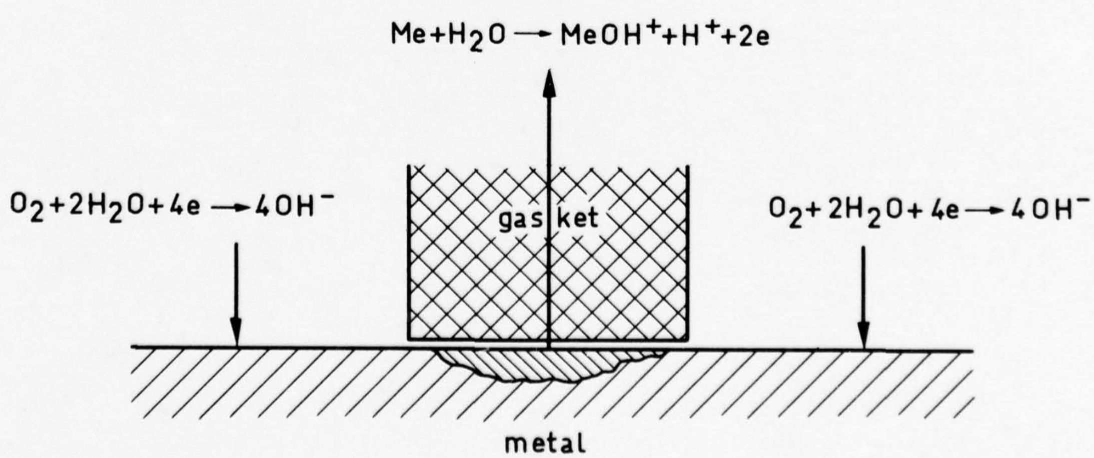

Fig. 6. Crevice corrosion.

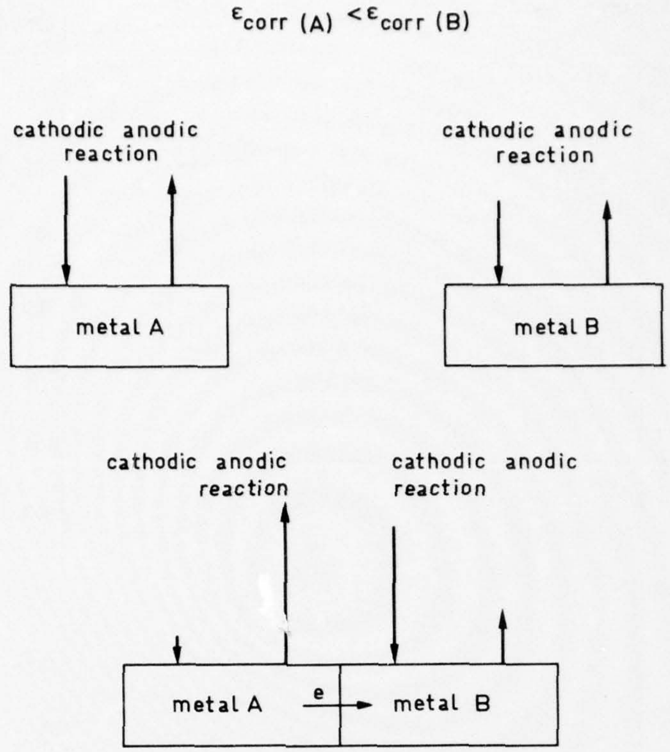

Fig. 7. Galvanic corrosion.

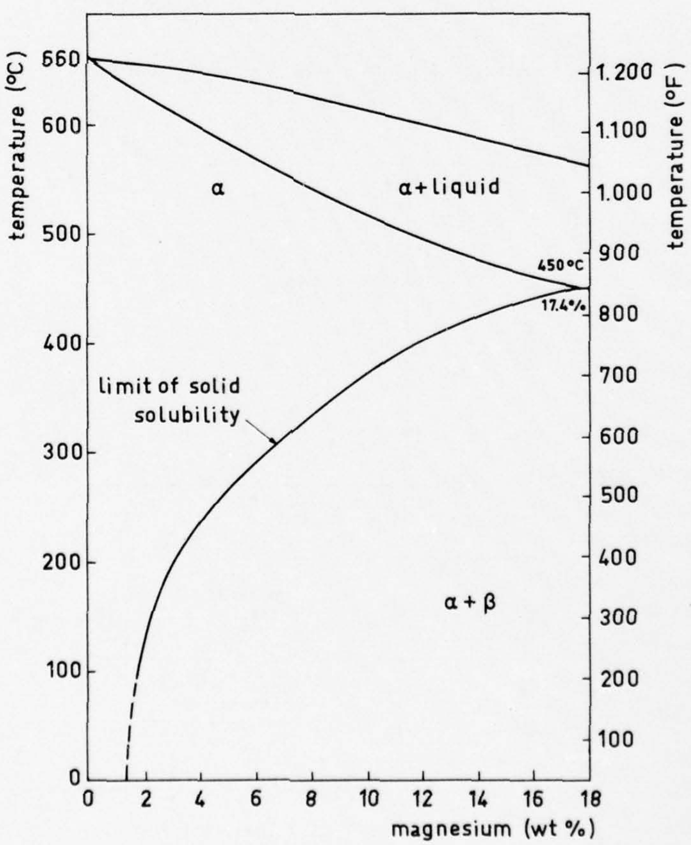

Fig. 8. Al-rich side of the Al-Mg phase diagram.

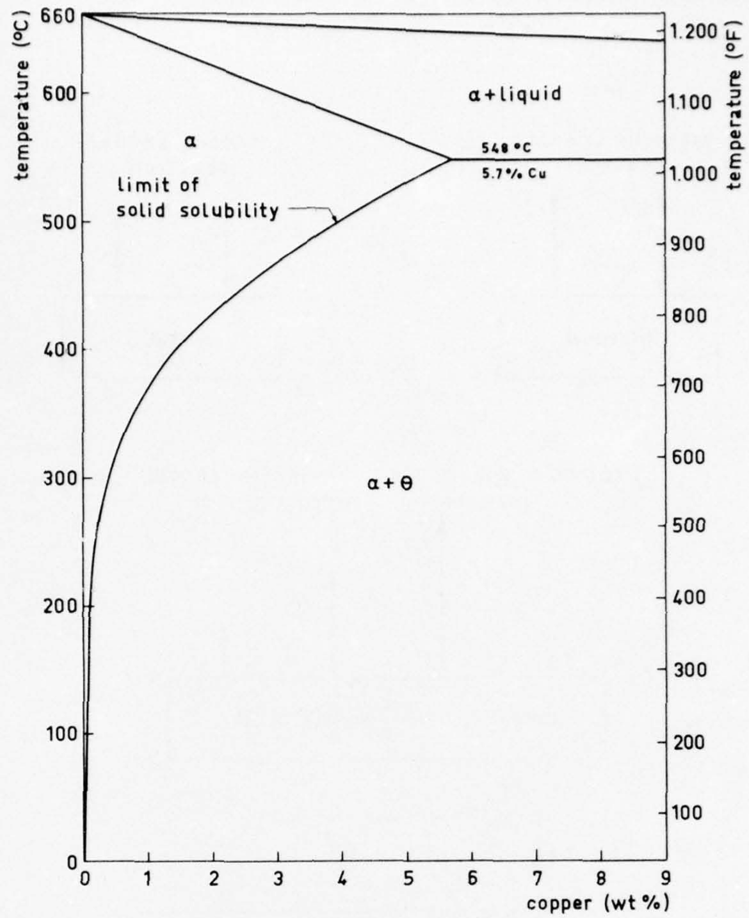

Fig. 9. Al-rich side of the Al-Cu phase diagram.

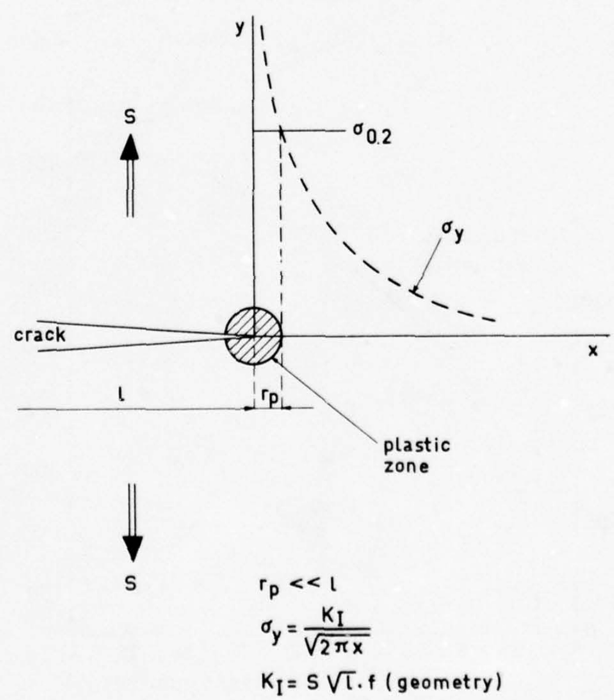

Fig. 10. Stress distribution at crack tip.

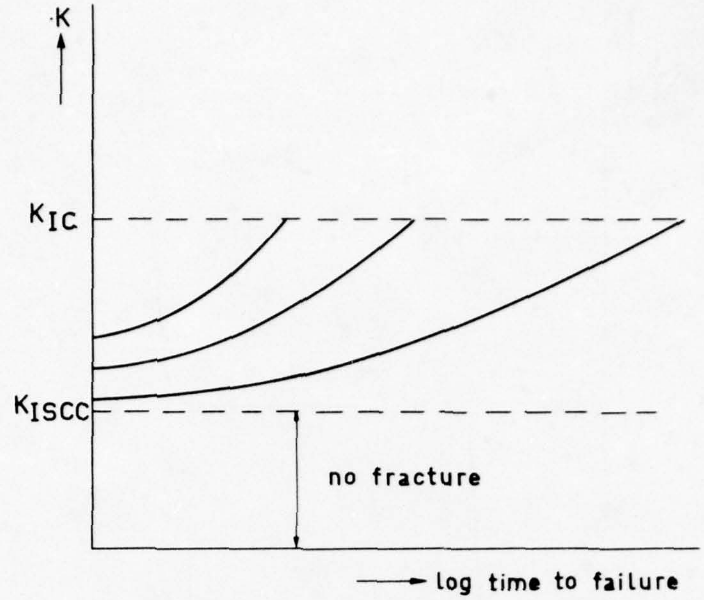

Fig. 11. Determination of critical stress level below which no s.c.c. occurs in a certain environment.

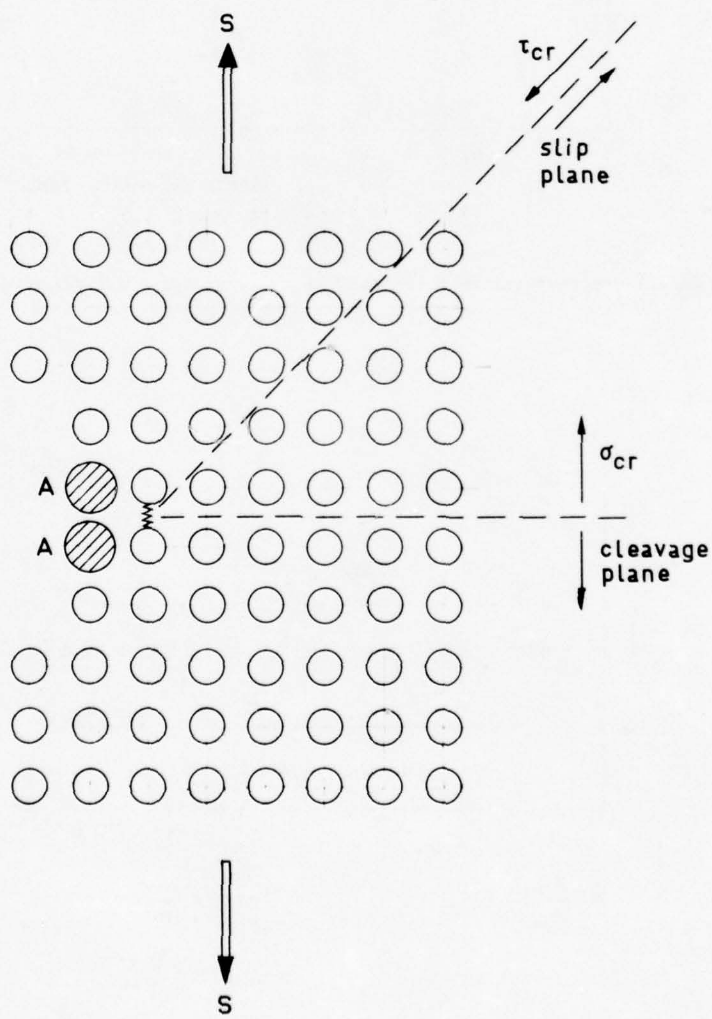

Fig. 12. Influence of adsorbates on the bond strength.

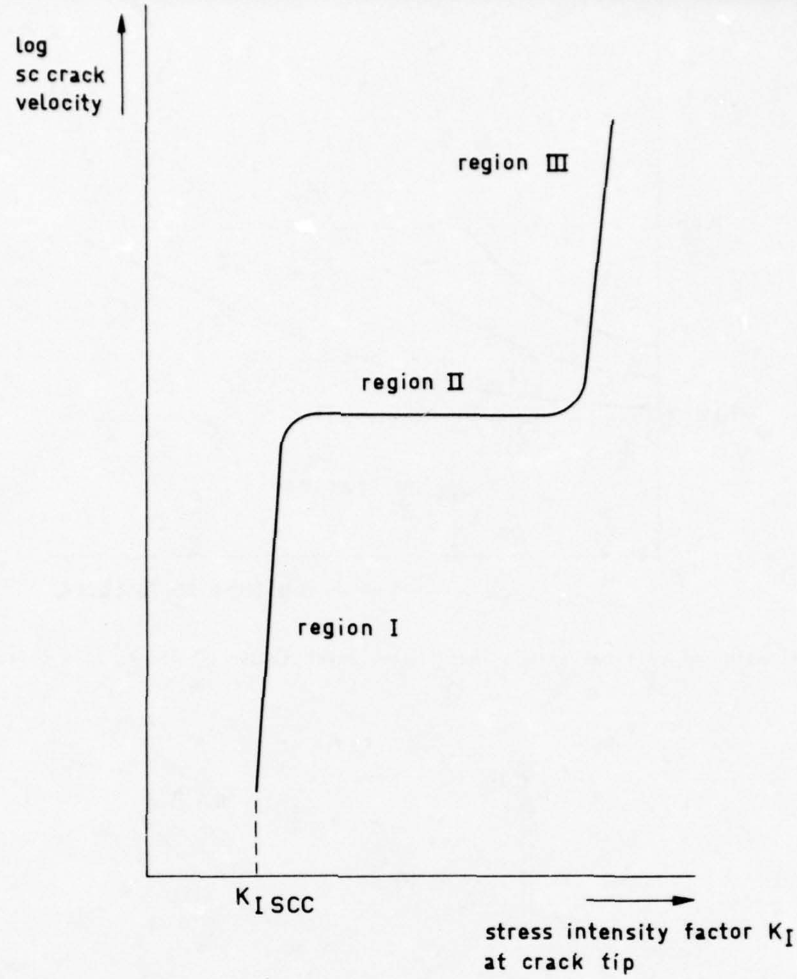

Fig. 13. Schematic representation s.c. crack velocity versus crack stress intensity.

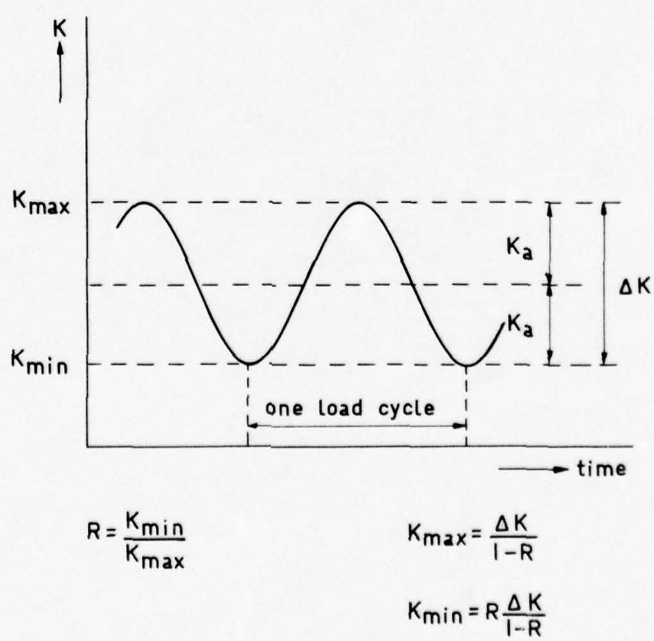

Fig. 14. Nomenclature used in fatigue.

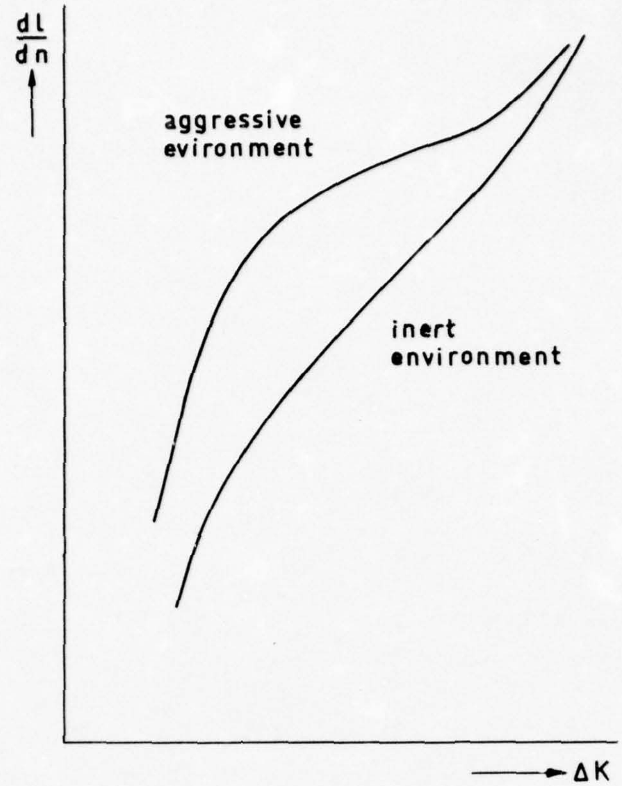

Fig. 15. Influence of an aggressive environment on fatigue crack growth in unit of length per load cycle versus ΔK.

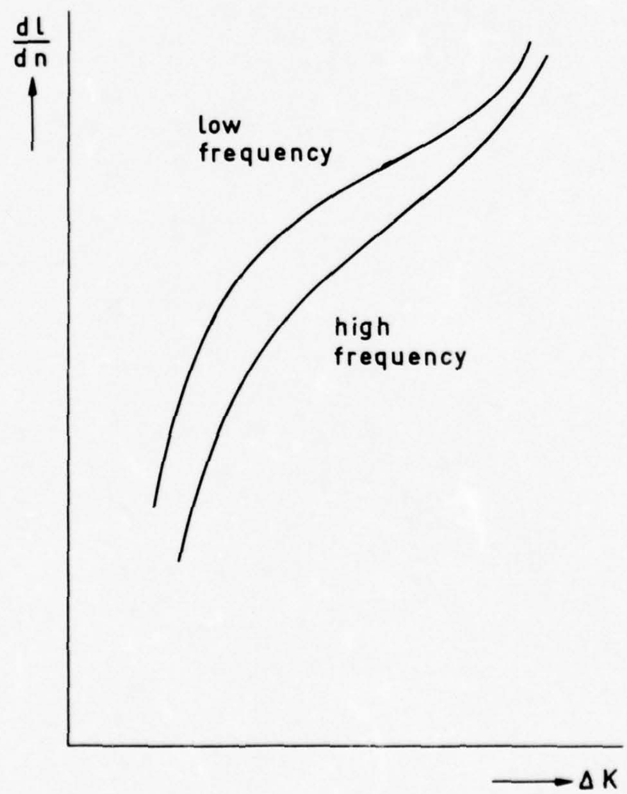

Fig. 16. Influence of loading frequency on fatigue crack growth in an aggressive environment.

ECONOMICS OF CORROSION

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1.0 INTRODUCTION

The combined annual maintenance for military aircraft is on the order of $1.5-2.0 billion. Various informed but informal estimates suggest that the costs directly associated with corrosion including repair and inspection are at least 25% of the maintenance costs. For the fiscal year 1975 the total of operation of maintenance of the air force was $10 billion. This is twice the 1965 figure while over the same period procurement costs have not changed significantly.

These high costs for both operation and maintenance (O&M), while the procurement costs have not changed significantly, have prompted a major concern for reducing the cost of maintenance operations. Reducing the cost of corrosion is only one of the avenues to be taken in this effort. Other costs are associated with retrofitting, inspections, replacement (tires), etc. A major component of all costs is labor.

At present it is impossible to define a real cost of corrosion owing to the complete lack of manipulable information. Uncertainties are described in this paper. Rather, I outlined some general considerations which should serve as a reasonable basis for improving the understanding of not only corrosion economics but the general problem of maintenance economics. The ideas herein, however, are prompted primarily by considerations of corrosion.

2.0 POSTULATES

In developing an understanding and plan for considering corrosion costs there is a series of postulates which can probably be accepted by most readers. It is not necessary to discuss these in detail for their validity is more or less self evident. These postulates are outlined below.

1. Any modification for improving corrosion resistance is cheaper to perform during initial manufacture and design than during a maintenance availability.
2. Any feature of corrosion resistance needed by the purchaser must be defined in the purchase specification.
3. For corrosion preventive features to be incorporated optimally, the corrosion organization must approve (sign off) drawings.
4. Sufficient information is available to prevent the occurrence of most corrosion induced failures; and for the cases where uncertainties exist the techniques of corrosion-mechanical testing which are available permit resolving these uncertainties.
5. The largest fraction of cost in maintenance operations is associated with the activities of people. Thus, improving the efficiency of the people should receive high priority.
6. Design features which facilitate maintainability and accessibility will reduce costs.
7. Most corrosion failures are related to one of the following:
   a. Availability of water or moisture.
   b. Presence of chlorides.
   c. Crevices.
   d. Use of very high strength materials.
   e. Unexpected sources of impurities.

3.0 UNCERTAINTIES AND PROBLEMS IN CALCULATIONS OF CORROSION COSTS

Those who have in the past calculated costs of corrosion have often labeled all preventive actions which were undertaken as costs of corrosion. This is not a valid approach. First, aircraft could not fly if substantially lower strength alloys were used which have improved resistance to SCC; the design is constrained to use high strength alloys for their fatigue strength. The use of protective coatings, inhibitors, shot peening, and drainage paths is not extra but is an integral part of using high strength aluminum alloys.

The only true cost of corrosion occurs when downtime or relatively low availability occurs and is more expensive than incorporating an initial design feature. This incremental difference is a cost of corrosion. Until information is tabulated in such terms any effort to assign a real cost of corrosion is vacuous.

In this connection one faces up to the fact that aerospace alloys are inherently reactive. Aluminum, titanium, and magnesium all have relatively low standard potentials relative to oxidation by water. Further, when alloys are used in these high strength conditions they have relatively low values of K_{I_c} and $K_{I_{scc}}$.

A second problem in calculating corrosion costs is the difficulty of extracting what failures are caused by corrosion. For example, fatigue is often initiated by localized corrosion problems such as pitting, SCC, intergranular attack or by fretting. The failure mode appears to be fatigue but the initiation is corrosion. So what is the cause? Wear is a high cost failure item; again, some wear is corrosion related. Also, environments play a synergistic role in fracture damage. Finally, some failures occur by corrosion processes which were actually not caused therefrom but resulted from a personnel mistake.

Most of the cost of maintenance is associated with inspection. In defining a true corrosion cost, that part of inspection which is corrosion-related should be assigned as a corrosion cost if the cost could be obviated by eliminating the inspection as a result of more reliable corrosion control.

Aircraft, in general, differ from other commercial equipment owing to the high mechanical components relative to the capacity of the alloys. Thus, a large fraction of the structure operates relatively close to the fatigue limits. This trend implies a high sensitivity to corrosion fatigue.

The military is often criticized for high maintenance and design costs relative to commercial practice. Some of this is no doubt justified and serious efforts should be initiated to incorporate commercial practices wherever possible. Nonetheless, many of the precautions and procedures which are used by the military derive from the nature of their mission. For example, a carrier based commercial airline would be a ludicrous idea, and commercial aircraft organizations would go to great lengths to avoid stack gases such as those on carriers.

Also, no one would think of high speed low altitude flights for commercial airlines as the pattern for modern attack planes. Such requirements increase the concern for chemical-mechanical integrity.

The electronic packages on military aircraft are inevitably more extensive because of the requirements of weapons system in addition to the usual systems for navigation and aircraft control. These electronic items are very sensitive to corrosion; and, further, their dense packing hinders accessibility.

Thus, there are certain costs which are implicit in military aircraft. These must be accepted as a starting point and certain corrosion related allowances follow therefrom.

4.0 AVENUES FOR REDUCING COSTS

The elements of cost relative to corrosion include--to varying extents--the following:

1. Frequency of inspections which are related to the need to repair corrosion-related damage.

2. Number of people requred for inspection and repair during a maintenance availability.

3. Time required to perform inspection and repair tasks.

4. Replacement parts and materials.

5. Modifications in design and materials leading to increased cost which arise from corrosion motivated problems.

6. Decrease in payload resulting from corrosion motivated allowances.

One of the clearest areas in which cost savings are possible relates to the maintenance personnel. Whatever will decrease the time and improve the effectiveness with which they perform their tasks will reduce costs. This implies the following:

1. Increasing the competence of personnel.

2. Improving accessibility to the aircraft.

3. Extra precautions to reduce necessary maintenance in difficult-to-reach areas.

4. Reducing the frequency and length of repair availabilities.

The feedback of repair information to design is useful in determining what actions are needed and which are excessive. Substantial improvements are probably possible in organizing the information feedback. Attention should be given to more defined judgements of the mode of failure. This information would provide bases for more precise judgement during the initial design.

In developing valid estimates of corrosion related costs more attention needs to be given to a broader spectrum. Specifically, the calculations need to include at least the following:

1. Direct cost of preventive procedures applied during manufacture including any weight penalties, extra labor, and testing for validation.

2. Savings in length and frequency of maintenance availabilities.

3. Incremental reduction in number of aircraft needed in a fleet as a result of reduced maintenance availabilities.

4. Probability of preventing total or major failures of aircraft.

Another contribution to reducing costs may derive from improved definitions of environments to which aircraft are exposed. This would include the following:

1. Time profile of relative humidity.

2. Analysis of ambient pollutants.

3. Analysis of aircraft surfaces to determine which pollutants are accumulated.

4. Chemical analysis of insulation, gaskets, machining lubricants, sealants, fuels.

While the subject of corrosion happens to be the primary objective of this discussion, other processes must be included as well. Thus, there is little value in emphasizing corrosion problems if the dominating issues are more related to wear and fatigue.

Finally, since most of the changes in design are incited by failures which occur in the field, increasing the precision, speed of acquisition, and breadth of this information is desirable. Accordingly, it appears highly desirable to take the following steps:

1. A corrosion reporting procedure should be developed by the air force and Navy where all information can be tabulated for both services using standard procedures. These procedures should be utilized by all NATO countries.

2. Ambient conditions including relative humidity, temperature, precipitation, and air-quality should be developed for all sites where aircraft are based. Again, this information should include all services and countries included in NATO activities. This information should then be related to the failure information to assess possibly causative relationships.

3. All damage modes including fatigue and wear should be assessed simultaneously with corrosion, and the causative and non-causative conditions should be delineated.

4. The experience of commercial fleets in all of the NATO countries should be included.

While early stages of implementing the above would certainly be tedious, the constant economic pressure which results from increasing O and M costs should be sufficient incentive to develop such a system.

5.0 ACKNOWLEDGEMENTS

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Corrosion in Airframes, Power Plants and Associated Aircraft Equipment

by

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Foreword

The writer's responsibilities are primarily concerned with materials problems in Naval aircraft ashore and afloat. It is inevitable therefore that many of the comments and opinions herein are concerned with this area of operation of military aircraft and with the needs for the highest possible standards of corrosion resistance to the marine environment.

This environment however is probably the most severe to which current aircraft are regularly exposed and with few exceptions good corrosion performance here will meet the requirement of almost all other operational theatres.

This paper expresses the opinions of the Author, and does not *necessarily represent* the official view of the Ministry of Defence.

INTRODUCTION

The title of this paper "Corrosion in Airframes, Power Plants and Aircraft Equipment" by definition invites a straightforward catalogue of classical instances of corrosion arising as a function of unsuitable material selection, inadequate protection, impoverished standards of maintenance, utilisation outside the predicted flight envelope or ambient condition etc. It was tempting to fall into the trap of producing merely selections from among the vast numbers of examples on record providing an easy and essentially non-controversial paper.

This however does little towards a critical assessment of the situation, and therefore the author sought first to re-examine the statement made in the preamble to this lecture series in the AGARD programme for 1976, and to see whether it is true that in fact most corrosion instances have been seen before, and could therefore have been prevented by application of known techniques.

A review of even a small percentage of corrosion arisings and the vast amount of literature on the subject confirms this factor of repetition - one has the feeling of being on a roundabout, and familiar scenes pass by from time to time with comparatively little change. The truth of the matter is that of all the multifarious defects which arise in each succeeding generation of aircraft, that of deterioration due to corrosion is probably the greatest single repeated problem. Furthermore in a large percentage of cases few if any totally new factors are involved, and the manifestation is merely a repetition of what has often been seen before.

In preparing any paper on the present state of the art, therefore, it is difficult to find some entirely new fundamental mechanism or set of circumstances which highlight a form of corrosion not seen previously or which exemplifies a mechanism hitherto unknown; by far the bulk of evidence arising is a reiteration of old examples.

Regrettably then the premise in the introductory preamble to this lecture series is all too true, and there is little doubt that on purely technical grounds many of the problems which have been both irksome and costly have existed over the years in several generations of aircraft. If not eliminated entirely some could have been spectacularly reduced if known preventive measures had been meticulously applied at the proper time, and with the requisite level of priority and importance, in a determined policy to attack the continually nagging corrosion problem.

SOME FACTORS AFFECTING THE PROBLEM

Before discussing specifically the sub-divisions of airframes, engines and equipment, there are a number of general factors involved in this whole subject which it is desired to highlight.

(i) Exposure

The kind of environment which in Naval operations has come to be regarded as in no way unusual, is exemplified in my first slide and operations involving conditions such as these both in the role of Anti-submarine warfare and Search and Rescue are commonplace. (1) Nor is the fixed wing aircraft operating from larger ships very much better off. By virtue of numbers embarked such aircraft frequently spend substantial portions of their operating lives above decks exposed for long periods to a saline atmosphere, often further polluted by funnel gases.

There is one very fundamental difference between defects arising due to corrosion and those other mechanical, operational, or stress-induced defects in aircraft, and that is that corrosion and the problems associated with it are substantially calendar dependent whereas the vast bulk of other potential defects are flying hour orientated to a much greater degree. Whether an aircraft flies a lot, or for some reason spends a fair amount of time on deck, has very little effect on the incidence of corrosion arisings, and some of the worst cases of corrosion which the author can recall have been in deck parked aircraft in carriers involved in fast transit passages where flying has been very limited.

The long ranging land based maritime aircraft frequently flying very long sorties over the sea, much of which may be at low level is also commonly in conditions of severe exposure and widespread outbreaks of corrosion can occur with the consequent difficulties and high costs of detection, and rectification. The problem is usually less severe in more benign conditions of operation but modern military aircraft have an increasingly wide spectrum of capability and the anti-corrosion standards employed need to be such that material performance is essentially unimpaired whatever the operating conditions.

Unless there has been a gross misapplication of material, or omission of protection, first signs of the onset of corrosion deterioration rarely arise in the early months of an aircraft's life. Protection is then at its best, usually non-damaged either by handling or operational conditions, and the aircraft is newly exposured to the environment. Such things as Intensive Flying Trials of new aircraft types or acceptance flying of newly delivered aircraft rarely if ever show either corrosion examples, or more importantly, the corrosion trends to be expected as the aircraft grows older.

(ii) Initial Standards

The standards of protection used at build are of necessity based on a combination of experience of previous generations of aircraft and on laboratory and field assessment of materials, processes and build techniques. However, in spite of the existence of procurement handbooks laying down design requirements for new aircraft, it is not a justifiable assumption either that all the very best techniques are universally applied or that they are applied with maximum efficiency. Over the years, in examining examples of corrosion arisings of all kinds the impression is gained that sometimes inadequate concern is given at the early design/material selection stage, to the need both for intrinsically high corrosion resistance in the material itself and for the application to it of, not one, but a combination of treatments at both component, sub-assembly and build stage, all designed to combine in meeting the total spectrum of corrosion performance requirements. It is not, in my submission, sound engineering judgement to employ in a severe environment, materials which have a high intrinsic susceptibility to one or other form of corrosion deterioration on the assumption that the exterior protection will prove the be-all and end-all. Furthermore it is essential to dispel any potential impression that maintenance routines should or will look after any deficiencies in initial material selection and protection. For many years now the military user of aircraft, frequently operating in a severely aggressive environment, has not only had to devote large amounts of maintenance efforts to ensuring continued material integrity but has come to regard this as the norm, and this is a costly, and in the long term totally unacceptable situation. Growing complexity of modern aircraft/weapon system combinations demands an amount of mechanical, electrical and electronic maintenance which is steadily increasing. Efforts are continually being directed to reducing the size of this maintenance task by improved reliability of equipment and it is of equal importance to do the same in respect of corrosion behaviour of materials and their protective coverings. Nowhere is this more severely felt than in aircraft operating in the maritime role and in particular the singleton aircraft or small air group operating from a relatively small ship. In the latter case limited man-accommodation precludes a maintenance party of other than the bare numerical minimum and ideally during the embarked stage there should preferably be no requirement at all for maintenance of the airframe structure to retain it in a corrosion free condition. The material selection/protection combination should be able to withstand the normal operating environment for a period of at least six months without the need for any form of treatment other than possible external cleaning to remove salt and soil.

We have not achieved this ideal at present and it is almost certainly one which can never fully be realised, but it should be striven for.

We have however become far too innured to the need for corrosion teams, corrosion kits, corrosion rectification or supplementary protection routines as a normal way of life. They are costly in man effort and time and they absorb effort needed in some of the other more immediate maintenance activities essential to operations.

This 'acceptance' of relatively high levels of man hours of anti-corrosion maintenance can result in a situation where basic improvements at build cease to be made, on the basis of 'no demand'. The materials engineer should always be in a situation where he questions the validity of what has gone before, with the user pressing his experience and making his requirements clear for the discarding of old practices where these have proved indifferent.

(iii) Feed back of information

Of course the problem is not one sided and it is by no means all a function of omissions or indifference at design or manufacture. Both designer and producer on the one hand, and operator on the other, are keenly desirous of improvement in this field but there is often insufficient feed back of information from the user to the manufacturer on the precise conditions of exposure, and the nature of the environment in which the equipment being designed is regularly and normally to be operated, and this may be particularly so in bought-out equipment or with sub contract design and manufacture.

It is a chastening and depressing thought that many engineers or materials specialists with high levels of design responsibility for an equipment for a sea-going role have never set foot in an aircraft-carrying ship. In the author's view the responsibility is reciprocal between operator and supplier, on the one hand to ensure feed back, not just of the corrosion defect but of

a precise assessment and statement of the conditions which have caused it, and on the other of a demand by design and materials engineers to see for themselves and be fully apprised of the conditions in which their brain-child may quite normally and reasonably expect to be operated. The environment itself changes little or not at all with the years, apart from changes perhaps in pollutant level, but the manner in which we operate military aircraft often changes with changes in offensive or defensive equipment. The spectrum may embrace greater or lesser degrees of high and low level operation, fast and slow speed, tropical, temperate and arctic exposure, short and long sortie patterns. A preponderance of operations in a particular environment will often profoundly affect the resulting corrosion behaviour and what was at one time applied to and may have been acceptable in one aircraft application will not necessarily be acceptable in another. It is all too easy to adopt a tacit acceptance with an air of inevitability that things have always been done this way but the facts of life are that corrosion containment merits increased emphasis as aircraft become more expensive, often less numerous, longer lifed, and capable of operating under more and more exacting conditions.

One aspect not always well appreciated is the enormous difference in aggressiveness of the environment attendant on the sea going aircraft or the helicopter operating regularly from ships in an anti-submarine or air sea rescue role, compared with the large passenger carrying or transport aircraft whose commonest glimpse of the sea may be from high altitude. This is not to suggest that the latter suffer no corrosion problems but they may be slower to arise and in the same period reach a lesser degree of severity.

(iv) Economics

The economics of corrosion are comprehensively dealt with elsewhere in this symposium but it is desired to make a brief reference to this aspect here purely from the point of view of the user.

The basic costs to the operator covering corrosion prevention rectification fall under two main headings, viz:

(a) Those involved within the original cost of equipment at the procurement stage;

and (b) Those arising in Service as part of the Cost of ownership.

Military users, and no doubt civil operators also, currently spend substantial amounts of time and money on corrosion prevention/rectification after equipment has been delivered for service and it is for very critical review to what degree this is disproportionate, and whether the cost of ownership aspect cannot be reduced by ensuring a superlative standard in the first instance. It is frequently difficult to determine precise orders of costs in Service because anti-corrosion work is not always separately recorded by the operator from other maintenance activities in a form whereby precise costs are easily derived.

In the Royal Navy the general heading "Husbandry" embraces all corrosion prevention and rectification but the term also covers work other than on corrosion, e.g. pulled rivets, loose clips, damaged fasteners etc. Recent economic exercises on certain aircraft types however have been much more specific and assessments have been made covering the degree of effort involved purely in corrosion prophylaxis and rectification at various stages from first line day to day squadron operations, through arisings pinpointed by three monthly and annual surveys and finally to that arising in P.B.M.(PAR) type operations. To cover the whole picture such assessments need to be expressed not only in terms of actual financial costs, but of the operational or logistic effects of withdrawing aircraft from Service for the performance of this work.

It needs little study however to appreciate that the number of aircraft needed within a given fleet to meet a given task can readily be adversely affected by the need to look for, find, temporarily or permanently rectify, or finally modify out, corrosion, and the more comprehensive the study, the clearer the picture becomes that the whole business is very costly.

The present balance of effort and cost distribution between the two headings noted above is challengeable. In the procurement of new aircraft first cost is often the major controlling factor to the detriment sometimes of the ultimate total through life cost, and there is no doubt that on occasion this can militate against the initial adoption of somewhat more expensive materials or techniques, irrespective of their longevity. This is a situation which has been experienced by most organisations from time to time. A paper on Aircraft Corrosion in the US Air Force (2) written in 1964 concluded with the statement "We have come to realise that $5000 worth

of the proper finish applied during production will most likely prevent $20,000 of replacement, repair, ... in the future life of the aircraft. It has become inevitable with world-wide operation and limited manpower for corrosion control that all aircraft must be protected to the utmost during production".

(v) Awareness of the Problem - Training

In common with other operators the Royal Navy have adopted a programme of specific anti-corrosion training for maintenance operators who are or will be involved in corrosion work (3). This covers sections of the basic training of newly joined ratings and also a Special Aircraft Maintenance Course covering aircraft corrosion which is attended by various ranks, NCOs and selected officers. Over the years since this was introduced in 1965 several hundred engineering and operating personnel have attended and in addition refresher courses are also given from time to time.

The ability to recognise the earliest signs of corrosion and an appreciation of the need for early rectification is of paramount importance in good squadron maintenance of aircraft, engines and equipment. There is naturally great difficulty in 'selling' the philosophy of preventive maintenance - maintainers who are hard pressed to carry out other essential mechanical or electrical operations are not easily persuaded to spend even a short amount of time in preventive maintenance on areas of known corrosion proneness but which are not yet actually suffering attack. Proper training in early recognition, effective control, and permanent restoration help to overcome this and as an added benefit a much more accurate appraisal of the cause is often obtained if serious arisings do occur. From a time-availability standpoint such training competes with all the other essential training facets involved in producing effective maintainers but it is money well spent.

In the area of aircraft design and manufacture however, particularly when one gets down to the small sub assembly stage, or minor equipment item, the impression is sometimes gained that there is often imperfect appreciation of the fundamental corrosion behaviour of many materials, both alone, and in combination, and in particular of the effects likely to arise with certain geometric forms and material conditions, when exposed in severe ambients.

It is useless preaching to the experienced materials engineer the gospel of better corrosion performance by enhanced design and material application. Materials specialists are, or should be, already converted but their role or relative importance in the design hierarchy may not always be of adequate status, and it is in this area of relationship where sometimes the battle needs to be fought.

AIRFRAMES - FIXED AND ROTARY WING

(i) General

In both the Royal Navy and the RAF an essential part of air operations involves low flying over the sea, and hence regular and frequent exposure to saline conditions. This applies both to helicopters engaged in Search and Rescue and Anti-Submarine operations, and also to fixed wing aircraft either carrier-borne or shore based. The corrosion problems are essentially similar, and the incidence of corrosion is generally higher in such aircraft than in those primarily associated with overland or higher altitude roles.

To a greater or lesser degree corrosion occurs in all types of aircraft irrespective of source, i.e. both British built, and those bought from overseas. It is exceedingly rare however to find an instance of corrosion presently occurring which is due to a cause, or which involves a fundamental mechanism which is not pretty well understood, and which generally has not been seen before.

The comment must be made however that what the user is currently seeing is the result of materials applications and protective techniques on aircraft which in many cases were originally designed up to ten years ago or even more. The question may then be asked to what extent in an aircraft being designed today will these problems still arise and can we sensibly hope that in today's "aircraft-on-the-drawing board" we might have fewer corrosion arisings and be able to reduce our man effort in preventive and restorative maintenance and hence cost-in-service? To answer this it is necessary to fall back on comparisons of corrosion behaviour over the years and whilst the picture is not all good, there are some areas of hope.

(ii) Airframe Structure - Aluminium Alloys

In the author's experience there have been broad changes in the form of corrosion manifestation over recent years, mainly as a result of changes inherent in design,

and the associated use of higher strength materials, generally in thicker sections.

Early post-war designs used substantial amounts of sheet alloys, in many cases alclad, in rivetted assemblies, and these tended to suffer corrosion in the form of surface attack and pitting in severe environments. This was frequently associated with the relatively indifferent performance of paint systems notably primers, but these earlier types suffered only to a limited degree from the problems of exfoliation corrosion and stress corrosion, again mainly as a function of their intrinsically thin section construction. There were exceptions in the case of extrusions and forgings but frequently these were in lower strength alloys compared to their modern counterparts and perhaps showed marginally less susceptibility at the lower stress levels. This is very much a generalisation and obviously exceptions can be quoted but this was the more general pattern of corrosion in RN aircraft at that time.

The advent of higher strength alloys, the design requirement of thicker skins often chemically milled, and later the move to machined plate introduced much more widely materials and sections with greater susceptibility to both exfoliation and stress corrosion and generally this has remained with us almost to the present day. Heavy section, higher strength alloys have been used extensively in the T6 condition in the search for maximum properties, and stress corrosion failures in some form or another have been experienced by many users, particularly where high sustained surface tensile stresses in the transverse direction have been involved. Since the latter part of the 1960s there has been a much better understanding of the limiting conditions for the use of these materials and a growing appreciation of the desirability where possible of using them in the double-aged condition. In many cases, in reworking existing aircraft and equipment it has been possible as a retrospective move to introduce re-heat treatment of some components to bring original T6 material to the T73 or T76 condition without change of scantlings and with substantially beneficial results.

There is within the last few years vastly improved documentation concerning the optimum design and fabrication conditions for use of materials in this class and the indications now are of greater appreciation of how best to use them. A recent design brochure of a commercial transport aircraft, detailing the materials selection shows the almost universal application of T73 or T76 temper conditions of the 7000 series light alloys and a paper presented at the US Tri-service Corrosion of Military Equipment Conference in 1974 shows how the same philosophy was being applied to a new fighter. (4)

Changes in design involving machined plate or slab and the associated reduction of the amount of thinner sheet materials employed has inevitably seen a commensurate reduction in the amount of clad aluminium alloy used. There is however no lack of appreciation of the value of cladding in this context and it is noteworthy that some new aircraft designs are still using cladding where possible. Cladding is sometimes dropped both for basic strength and fatigue reasons and it is a nice balance of choice between corrosion performance and strength/weight considerations. Although the inherent value of cladding is appreciated, in the author's experience, improvements in pre-treatment and primer performance have made this a less essential prerequisite of naval aircraft design than once was the case. Nevertheless on balance cladding is preferred where possible.

Whilst there is little doubt that the use of unclad alloys has affected the corrosion situation, changes in the type of fastening of the thicker plate materials have effected a prime contribution and it is probably true to say that a substantial part of the corrosion seen in modern heavy gauge aircraft structures commences at changes of sections and at countersinks. In highly stressed areas, with rows of steel fasteners in large countersinks, the bugbear of exfoliation corrosion exacerbated by the dissimilar metal contact has been a growing problem and again this is worse in some alloy tempers. Generally those materials and temper conditions with the lowest resistance to stress corrosion are also most susceptible to exfoliation and the improvements to both conditions imparted by double ageing treatments of the T76 variety are to be desired wherever possible.

Unfortunately among aircraft currently in service there exists considerable material which is not in the most corrosion resistant condition in the first instance following design requirements where maximum physical properties were paramount, and we now have to live with this. It undoubtedly contributes significantly to the present corrosion situation.

The subject of optimum alloy selection and temper is well covered in the literature and there is no point in going into extended detail here but ample opportunity exists for future equipment to show the advantages to be gained by this means over those pertaining in the past if new designs can be produced

in which the slightly lower maximum stress properties of the double aged materials are acceptable.

The exfoliation problem is by no means confined only to the higher strength T6 temper materials, some alloys in the naturally aged state, in heavy sections, are also very susceptible. As an example a recent UK maritime aircraft with long range and with an operating pattern covering both high and low level operations over the sea has exhibited classic exfoliation corrosion in the areas of access panels in the wing. The material concerned is a 2024 type alloy in plate form solution treated, stretched and naturally aged and also in sheet form solution treated and naturally aged. The plate has relatively low resistance to exfoliation, the sheet is slightly better. The design of the joint involved is one in which extensive end grain is exposed, and classical exfoliation has occurred. At build all the items were anodised, epoxy primed, and assembled with a molybdenum disulphide grease at the faying surfaces as an anti-fretting measure. The incidence of corrosion to varying degrees has been detected in over 50% of the fleet and has turned out to be an exfoliation rather than a fretting problem. As a result the M_oS_2 grease has now been deleted and substituted by a chromate pigmented jointing compound, with a final fillet seal of chromate pigmented elastomeric type polyurethane applied at the narrow chamfer between wing skin and panel. On panels significantly corroded a repair scheme involving a modified joint geometry has had to be devised. As an additional precaution water displacing fluid is sprayed around the joint after flight. Although constituting some maintenance penalty to the operator this latter is acceptable since the same fluid is used in the engine wash/inhibition cycle also.

This situation is in no way atypical of similar arisings on other aircraft types and there can be few if any materials engineers who are not familiar with the now classic condition of exfoliation corrosion commencing at countersunk fasteners and cut edges. Although in the author's experience these locations tend to figure highly in the corrosion pattern they are by no means the only locations of trouble. Laminar corrosion on occasion may start in the centre of a panel or extrusion away from any apparent change of section. From a point of view of rectification this adds to the difficulty, - it frequently involves the scalping of controlled amounts of metal from the area, and perhaps the fitting of oversized fasteners. Clearly there are severe limitations to what can be done in this respect but many examples have been seen where surprising amounts of material have been removed in the effort to combat the problem. A further difficulty is fully effective monitoring to ensure complete removal of exfoliating metal and at present it is extremely difficult to be 100% certain that this has been achieved. Improvements in the treatment of fastener/countersink areas are an important requirement in future equipment and a complete answer may be relatively costly.

Such treatments as ion vapour deposition of aluminium both on fasteners and on countersinks have been proposed and used to a limited degree. (5) Their beneficial effect is readily demonstrated but the capital cost of plant is high if large components are to be treated.

(iii) Magnesium Alloys

Magnesium as an aircraft structural material, in sheet form or thin plate, is generally a maintenance nightmare in aircraft operating close to or over the sea. The extent to which it has been used in the past particularly in the helicopter role has contributed in no small measure to the extensive corrosion bill of several Navies and Air Forces. Of necessity protective schemes for magnesium of a very high order have been developed and the condition has to some degree been contained but at great cost and it is essentially a losing battle, particularly with increasing aircraft lives. The performance of magnesium particularly exemplifies the difference in exposure conditions and hence corrosion behaviour of aircraft operating primarily in the marine role compared to those used always in a benign and dry atmosphere.

Although the RN still operate helicopters with considerable amounts of magnesium, it is British future policy to avoid its use unless supreme overriding considerations leave no alternative. The attitude is not one of a total ban but the case for adoption of the material must be very good. The benefits of magnesium alloys are well appreciated, - apart from intrinsic good strength/weight, their castability, freedom from intergranular corrosion and the ability to retain good strength at medium operating temperatures are all beneficial and are taken into account when considering the material for any specific application.

As a principal magnesium is unacceptable in areas which are inaccessible for examination and/or treatment, and in general if accepted in any new design it is more likely to be in 'oil-washed' areas such as internal gearboxes etc., and then only in relatively massive form.

(iv) Ferrous Materials

With a few exceptions notably in undercarriages the current generation of RN aircraft contain only very limited quantities of ultra high strength steels. Generally protection of medium and high tensile steels has been by conventionally deposited cadmium and latterly in some applications ion vapour deposited cadmium. These have commonly been chromate passivated and painted and on the whole the system has been reasonably satisfactory. Corrosion, and occasionally stress corrosion does occur however and there is a continual requirement to ensure the integrity of protective coatings and this is a steady commitment of effort as indeed with other metals. There have been few catastrophic failures, and where there has been experience of severe corrosion there is sometimes evidence of imperfect choice of protective method in the first place, possibly as a result of lack of appreciation of the potential severity of the conditions in the area concerned. Recently in two widely differing types of aircraft there have been fatigue failures of main undercarriage components initiated from local pitting. Also it is not uncommon to experience corrosion on internal surfaces ostensibly out of direct contact with the operating environment and as an example a problem of internal corrosion in tubular steel construction of tail booms, engine mountings and drive shafts of Army light helicopters occurred a year or two ago. This was directly attributable to poor standards of internal protection and proved a costly exercise. A further example is given in the review of case histories in a later paper.

Specific structural items, plated, painted, and well maintained, usually behave reasonably well. This does not always extend however to the multiplicity of standard AGS parts, nuts, bolts, clips, fasteners, etc. where undoubtedly plating thickness on occasions is marginal. There is an upper limit of temperature for application of cadmium protection to steels, and above about 200°C other methods are needed - I.V.D. aluminium has been mentioned, phosphate treatments based on a manganese phosphate process have some use and there is also current interest in UK in the use of electrophoretically applied paint coatings containing metallic pigmentation and having sacrificial protective capability. This is a promising area particularly for fasteners, for items of complex shape and where the temperatures involved do not permit cadmium. The material was first developed for engine applications but clearly is not limited to this use. There is currently a growing aversion to cadmium on environmental grounds and this is an international problem. If it continues with the present emphasis it is going to mean that we shall have to find a satisfactory substitute in the very near future. In UK there has been consideration of the use of zinc as alternative to cadmium for the protection of steels and certainly we used this during the war. It is however less satisfactory for use in saline environments and on commensurate thickness basis as a sacrificial protective is consumed more rapidly than cadmium. It is also unacceptable in certain specialised locations where it is in contact with aviation kerosine.

(v) Titanium Alloys

Relatively limited use has been made of titanium alloys in current airframes in RN Service, and where they have been used the 6 Al 4Va alloy has been the predominant material, aside from commercially pure titanium. From a corrosion standpoint we have had no serious problems, provided controlled handling, and avoidance of critical contacts e.g. methanol, or cadmium plating in high surface loaded areas etc., is ensured. In these applications the materials have almost universally been room temperature operated, and this has not been a significant corrosion area.

(vi) Paint Protective Systems for Airframes

There has been one major step forward in the matter of airframe protection in the past few years, and this has been the advent of primers based on epoxide resins with leachable chromate pigmentation; in the opinion of the author this has been one of the outstanding improvements in materials for protection of aircraft since the war. The ability of a primer to release at a controlled rate soluble chromate ions at the seat of a micro break and thus to exert some inhibitive influence in the presence of an electrolyte is of paramount importance, and modern polyamide cured epoxy primers of this kind are now almost universally used in British aircraft. There is also widespread agreement on the desirability wherever possible to give all components full corrosion protection, including primer at the detail stage. At no time in its subsequent life will a component be as clean, nor will its surface pre-treatment ever again be in as good and 'receptive' a condition as when first produced and this is the best time to prime with a high duty system. (6)

In the laboratory which I represent we strongly favour the use of primers of this type for application to all types of aluminium alloy, magnesium alloy, and cadmium plated and passivated steel. Parts should be in the fully

finished state and the primer although normally and perfectly acceptably air drying, is beneficially forced dried by low temperature baking at 120°C. Drying time is shortened and subsequent handling without damage facilitated and we have found no finish adhesion problems following this practice.

Finished spares for military aircraft which are normally to be painted should always be complete up to and including the primer stage as a part of original manufacture. They should never be left in an unprimed and temporarily protected condition if this can be avoided. Fully primed items ensure that on assembly critical interfaces are paint protected prior to being coated with inter-faying compounds.

The practice on assembly of using jointing or inter-faying compounds has often been a vexed one from a production standpoint and is one of the areas where differences have existed in the past between aircraft manufactured in one country and another. There is no doubt whatever that properly used the technique is beneficial, but it needs proper production control and the right choice of materials to obtain the full benefits.

A fully protective primer and jointing system demands good adhesion over a sound pre-treatment, leachability, mechanical strength, chemical resistance, and flexibility, and the achievement of these is an essential prerequisite for the first phase of a high standard of paint protection. Overcoating of this basic primer system may require a variety of types of coating depending on specific conditions - for example integral fuel tanks will need further protection and a typical system involves a polysulphide or polyurethane material possibly overcoated with Buna N. In tank coats the property of water resistance and resistance to microbiological corrosion is required.

On normal external surfaces of aircraft however choice of one of a number of finishes may be involved. For some years it has been standard practice in the exterior finishing of RN aircraft to use a solvent acrylic finish over a polyamide cured leachable chromate pigmented primer. This acrylic finish was originally used as part of a heavy weight, all-white anti-flash system and in practice the scheme, aside from its good reflectivity, gave very good corrosion protection. The finish was subsequently developed in a range of standard camouflage colours and for over ten years has been used on virtually all RN aircraft. (7) It has been singularly successful and possesses one outstanding attribute in that it is easily and readily stripped from the primer without damage using either Toluene or a mild mixed solvent stripper. (8) There are many occasions when finish removal is needed, for changes of role or environment, alterations of camouflage etc., or merely for aesthetic refurbishing. There is often no fundamental need to remove primer down to bare metal, in fact the reverse is often the case and in the opinion of the author the use of aggressive paint removers, acid catalysed or phenol modified, can often leave a legacy of joint pollution adverse to the adhesion and subsequent performance of repainted coatings. This RN policy of using selectively strippable acrylic over leachable chromate epoxy primer has been religiously followed with generally satisfactory results on all the normal materials of airframe construction both internal and external. It is a system which is now being adopted by the Royal Air Force on a substantial number of their aircraft. Apart from certain specialised anti-erosion coatings, the RN have never employed polyurethane finishes although these have been used by the Army and RAF in UK. RN objections have been on the grounds of toxicity, however low, and the fact that for Naval aircraft there is no requirement for a high gloss. There is however the paramount RN requirement for ready and effective selective stripping on all aircraft but particularly on helicopters where removal of paint from magnesium surfaces without damage to the original chromate film is impossible with non selectively strippable finishes and where repainting by overcoating would be objectionable on grounds of weight addition. Hence the original adoption of a selectively strippable acrylic and its steadily increasing use. The scheme is economically attractive, overall costs and time involved of stripping and refinishing are significantly less than total paint removal to bare metal and complete repainting. It is used on all aircraft types, both helicopter and fixed wing, and its Service performance has been very good. There are very few limitations on its application, - it is perfectly resistant to conventional ester type lubricants but it should be noted that acrylic finishes of this type are not resistant to spillage of phosphate ester type hydraulic fluids. Since these latter are not in use in the RN it is no problem to us.

A further example of its use - All RN Phantom radomes are now finished in this scheme - performance is very satisfactory, there is no adverse effect on radar transparency in the wavebands in which we are concerned and it is simple to retouch adventitious in-service damage. For ease of rework and touch-up in the field a simple scheme of this sort has better chance of success than one requiring multiple packs and accurate mixing and this is an important factor of local corrosion rectification in service.

(vii) Geometric Considerations - Interior Surfaces

In the matter of airframe corrosion there is always the need for considering the contribution of geometry towards corrosion behaviour.

The production of ideal geometry of airframe design to minimize corrosion is not easy. Certainly at the design stage pocketing can be minimised by appropriate angling of stringers and stiffeners and by provision of drainage holes. These latter, however, cannot invariably be sited at the ideal point for structural strength reasons and whilst allowing removal of bulk accumulations the 'residual trace' of contaminant can still constitute a problem. Unfortunately hole edges are not always the easiest things to protect, they are often sharp and paint tends to be thin on such edges. Areas often exist where high duty systems may be necessary to cater for internal drainage either of water or other corrosive fluids and such areas as battery spaces and galley areas in transport aircraft need levels of protection commensurate with the nature and frequency of spillage of the corroding medium. Very often in these areas there may be a requirement for both erosion and corrosion protection but where the former is needed it also requires a very high level of corrosion inhibition first. Some high duty nylon coatings are valuable erosion resistant protectives.

Internal surfaces of 'closed' box sections can be problematic and slush or fill and drain techniques whilst helping are not easy to control to ensure perfect coverage in complex assemblies. Generally electrophoretic painting has not been used in UK in aircraft construction to date for fairly obvious reasons, but there may be specialist applications of this method in the future.

There has been some recent study in UK of the preservation of internal surfaces of 'box' or closed sections, and where these are totally fabricated from sub-components priming at the detail stage can best meet the case. This does not apply to tubular welded construction however and there are on record examples of serious corrosion arisings in such structures. Various techniques may be used either in lieu of, or in addition to painting, and modern water displacing fluids followed by wax-thickened petroleum based preservatives are giving good protection in such areas. It may well be that in other areas where drain holes are located as part of the design, the judicious coating of the area internally in the vicinity of the hole with such a supplementary protection would go far to eliminate corrosion due to residual traces of non-drainable fluid.

(viii) The Use of Temporary or Supplementary Preservatives in Aircraft

For several years the Fleet Air Arm of the Royal Navy has been the largest user of high duty water displacing fluids of any of the three Services, and as a palliative for corrosion where salt water is involved their use has been invaluable. (9) (10) It is true to say that one earlier mark of helicopter (a magnesium balloon on the end of a windmill!) was only able to be retained in service by the judicious but extensive use of regular libations of water displacing fluids over the total exterior, and parts of the interior of the structure.

Water displacing fluids have been available for many years, but the higher duty materials which both displace water effectively and confer some subsequent corrosion protection to exposed metal surfaces are of more recent origin. It is standard practice to use these materials on a wide range of mechanisms and equipment both moving and static and with RN helicopters at sea, water displacing fluids are regularly used for overall wiping down after aircraft washing following severe over-water operation.

Their use in this context is surprisingly economical, volumes consumed per aircraft are not large and the benefits to be obtained are substantial. It is necessary however to emphasise to the maintainers that sparing application is all that is necessary and to dispel the often held belief that the benefit obtained is proportional to the amount used.

Modern materials have the virtue of displacing salt water as well as fresh without 'salting-out'. These fluids however are essentially 'supplementary' preservatives and in our philosophy are used to support what should be an intrinsically good protective system initially - their primary action is to dispel residual moisture, saline or otherwise, from crevices, discontinuities etc. where the problem often starts. The heavier weight wax thickened, petroleum based preservatives which do possess some intrinsic water displacing capabilities albeit less effective than the more mobile fluids are being used in some specific locations as more permanent protectives particularly on internal surfaces in areas of infrequent access.

ENGINE CORROSION CONSIDERATIONS

The gas turbine, operating in a corrosive environment, is prone to corrosion both externally and internally, on both static and dynamic components.

Apart from basic requirements for engines and associated components to be fully protected, UK Design and Procurement specifications for engines lay down mandatory requirements for two major series of salt ingestion tests to determine the corrosion behaviour of all new engine types. (11)

These cover static periods of exposure after salt water spraying and ingestion with copious salt water residual in the engine, and running tests involving measured ingestion of salt water and the effect on performance, and restored performance after washing. Finally the strip condition of all components after both tests is determined.

Such testing, whilst severe and searching, is a compromise in time and can only really cover the relatively short term effect. Tests are usually performed on engines of a new build standard when any protection on surfaces is fresh and relatively unaffected by thermal excursions, erosion etc. They cannot simulate the long term effects of continual usage over many hundreds of hours when erosion, or thermal shocking of protective coatings and changes in hot component conditions have taken place due to deposits, oxide films, distortion etc.

Whilst much can be done therefore to ensure that initial standards of protection have good integrity, short term testing gives limited information on long life performance under the actual conditions of operation. Laboratory testing of individual components or coupon test pieces helps to complete the picture but in the ultimate, endurance testing and Service performance is the final arbiter.

Modern engines inevitably contain a multiplicity of dissimilar metals in contact not all of which have high intrinsic corrosion resistance under all conditions of operation. At one time standards of protection in military engines were significantly lower than currently applies and under marine conditions both internal and external corrosion was commonplace - often resulting in premature removal from service. The writer has seen many more than single figure instances of perforated compressor casings, burst cooling air manifolds, failed blades from corrosion pits, and corrosion 'frozen' stator segments which could not be removed from stator slots without damage. The situation has undoubtedly improved, particularly when it is remembered that the present day overhaul lives are longer compared with those pertaining 10 - 15 years ago, and this is a product both of improvements in material selection and protection, and vastly improved in-service maintenance in particular in the matter of compressor washing and inhibition.

The use of materials with intrinsically good corrosion resistance is as important in the engine context as the airframe. We still have some engines in use with magnesium alloy compressor outer casings, but the high cost of protection and disproportionate effort needed to control corrosion has led to their elimination from new designs. In current engines, steels of the 410, AM355 and FV520 variety figure largely in the air washed areas of engines. The classic 12% Chromium type martensitic stainless steel has been used for rotor and stator blading for many years in a variety of engines, and under relatively 'ordinary' conditions of exposure gives good service for long periods. However its susceptibility to pitting corrosion in a saline atmosphere is well known, particularly under conditions of relatively low access of atmospheric oxygen such as may exist under a deposit or a salt incrustation. Corrosion of blading, discs etc. in this class of steel has in the past caused enormous cost on overhaul of engines world wide, and the prevailing logistics of blade and vane rejection are still far from acceptable.

There are innumerable examples in most people's experience of the type of corrosion-induced failure in which fatigue cracking from pits in type 410 stainless has occurred. The problem may largely be overcome by changing to a much more highly alloyed material e.g. Inco 718 but with the attendant large increase in first cost, or it may be alleviated by coating the 12% Cr type steels with either a paint coating or a diffusion or overlay coating having sacrificial capability.

Paint coatings of various types but mostly of the epoxy-silicone variety found favour at one time as blade protectives and are still used to some extent. These are variously pigmented, and are sometimes fortified with aluminium pigmentation as an aid to thermal stability at the hotter end. Such coatings are not sacrificial and rely essentially on their continuity and barrier characteristics. On relatively short overhaul lives they confer some degree of protection and in a non-metallic pigmented form used in low pressure compressor stages they give smooth coatings with low impediment to gas flow, and are relatively easy to clean during compressor washing. Such coatings are still in service but they suffer the problem of all normal paint coatings on tight tolerance surfaces and on sharp edges of having either inadequate thickness to protect effectively, or being unable to be used at all for dimensional reasons, and with longer engine lives erosion performance is inadequate.

Alternative types of protective coating have improved and continue to do so and the present situation on type 410 stainless steel protection falls mainly into two categories viz. 'paint' or 'overlay' type coatings using aqueous based aluminium filled ceramic type formulations which with suitable post-application heat treatment and/or burnishing produce thin and, allegedly, sacrificial protection, and diffusion type coatings, produced at lower temperatures than conventional pack aluminising and resulting in an aluminide layer which is subsequently sealed using a very thin fused inorganic seal. It is claimed that these coatings are sacrificial at microdiscontinuities but this is not universally acknowledged.

The superior protective value of these coatings under ASTM B117 salt spray conditions compared to previously employed paint coatings is beyond question and there is a large and growing volume of operational experience to support this. As to the absolute merits of the two types, we have as yet no direct RN operating experience of the diffusion type coatings, but on RAF Service engines operating under severe exposure conditions the merits of the aluminium filled ceramic 'paint' have been well borne out and coatings of this kind are now being adopted in some new RN engines. (12)

The diffusion type coatings have several very special merits - their ease of application to complex shapes and in blade slots, screw threads and areas very difficult of access to paint make them attractive, and recent examples which have been seen on helicopter engines operated for two years under marine conditions in the Baltic have shown excellent performance.

There is thus potentially, and in practice on some newer engines, considerable improvement in compressor corrosion performance largely as a result of up to date coatings, and on an economic note they are generally substantially cheaper to introduce than changing to a much more highly alloyed material. Obviously operational experience under severe conditions will prove the point in individiual cases but the performance of these coatings on existing engines has already largely done this and their increased adoption is justified on most ferritic type alloys in air washed spaces of the engine and on shafts, discs casings etc.

As an aside, the testing of coatings of this type to reproduce realistically the type of deterioration experienced in practice presents some problems.

One approach in UK in laboratory testing coatings of this sort is to use not only the conventional elevated temperature salt spray but also a "ten cycle corrosion test". (13) This consists of exposing the test panel or component to dry heat at 450°C for two hours followed by exposure for 22 hours to continuous room temperature salt spray.

This cycle is repeated ten times and the component then examined. It has proved particularly searching, certainly more so than straight salt spray exposure, and generally the results have been reasonably analagous with practice.

Concerning titanium alloys in compressor areas, the bulk of RN experience has been with the 6 Al 4 Va alloy. We have been well aware of the extensive laboratory work done on hot salt stress corrosion cracking of Titanium alloys, but to the author's knowledge have never experienced a failure of this type in Service. There have been many years of operation of engines with titanium alloy blading in a number of stages in the compressor, and certainly some sections of these have regularly been functioning in temperatures well over 250°C and in conditions where salt ingestion has been of such severity as to cause severe pitting corrosion of 12% chromium steels in the same engine, but in no case have we had corrosion failures in titanium.

From the user's point of view the minimising of internal corrosion in engines operating over the sea is largely a matter of compressor washing and there is no doubt that this is a routine which needs meticulous and thorough application to be effective. Poor or slipshod operation can be positively dangerous since salt residues are washed into crevices from which, once dried, they may then be less easy to remove.

In severe operating conditions daily compressor washing may be necessary both for restoration of power lost from salt deposit accretion, and for corrosion amelioration.

Washing treatments vary depending on the type of fouling - for removal of salt, fresh water injected at a fairly high rate is effective, but if deposits are sooty or oily some form of detergent wash may be needed. The use of these latter materials does not always find favour with the manufacturers of some sealed-type diffusion coatings.

In the matter of hot end corrosion the literature is rich with information on the deterioration of turbine blade alloys under severe chloride ingestion and in the presence of sulphur, either from the fuel or as a component of sea water. As noted by the Lecture Series Director, this is a major field of its own and it is not proposed to discuss the mechanism of hot end corrosion here. In any event Experimenters do not always agree on the various mechanisms which have been proposed. Many hot end corrosion effects are markedly temperature dependent, the effect of sulphates on both austenitic and ferritic steels is much more severe above 750°C and if any reducing conditions are present the attack can be exceptionally severe. The added presence of small amounts of chloride can produce volatile $Cr\ Cl_3$ which destroys the protective oxide layer and allows further reaction with sulphates to occur.

Control of hot end corrosion has been steadily improved by alloy development, and by blade coatings of both the diffusion and overlay type. The most commonly used coatings have been aluminised layers deposited by pack deposition, and essentially on nickel based alloys these consist of varying composition layers down to the matrix. Present RN operating experience on existing in-service engine types is confined to the straight pack-aluminised type coatings although there is growing development experience with chrome aluminised and the so called CoCrAlY type coatings particularly for marine gas turbine use.

The range of coatings is wide - current work on Pt-Al coatings is reputed to indicate some promise although the precise mechanism of protection is not entirely clear, and aluminium silicon coatings have been used proprietorally on some engines.

There is no doubt that this is an area where current coating development will have important effects on the long term performance of hot-end components and to some extent this is being stimulated also by the need for coatings for engines of the marine gas turbine type where temperatures are lower, and hence creep lives substantially longer but by definition exposure to a corrosive environment is also much longer. It is not easy to see the next logical step of progression but improved coating technology is of profound importance in controlling corrosion particularly as life extension of engines is achieved.

AIRCRAFT EQUIPMENT

It was originally intended that this section of the paper should deal with corrosion deterioration in electronics but in this I have only very limited experience and I cannot comment critically. It is hoped that the discussion may have a contribution to make on this aspect. Much electronic equipment is of the sealed variety, and in the past corrosion was sometimes derived from conditions existing within the boundary of the seal. The type of attack associated with the evolution of corrosive vapours from imperfectly, or newly cured organics, and often attributed to aldehydes or lower fatty acids is now rarely seen, although examples do occasionally arise. Corrosion due to phenol, formaldehyde, formic or acetic acids derived from glues or some types of timber has been drastically reduced largely due to a better understanding of the subject and to changes in packaging methods and standards. Firm instructions on the avoidance of this type of problem were promulgated in UK some years ago and this seems to be an action which has borne fruit. (14)

The field of aircraft electrics however is one in which a plethora of dissimilar metals in contact exists, often with limited subsequent protection. Whether the design assumption is that a component buried within the aircraft interior has greater immunity is not known but if so it is an unwise philosophy particularly in marine operations.

An example which may be of interest is a fuel tank capacitor unit which in one squadron of eight aircraft was exhibiting corrosion in seven cases. The item showed very severe corrosion on the base plate which was made in aluminium alloy 6061 in the T6 condition and this had been electroplated with copper presumably after pre-treatment and then given a moderately thick tin coating, - by what means was not known to us. The object was to permit attachment of the terminal box by soft soldering - easy workshop practice but in the event of a breakdown in the coating in the presence of an electrolyte the probability of corrosion occurring in service was high. This was on an aircraft type in use in both RN and RAF - all the RN aircraft had been carrier borne and all showed the trouble, none of the RAF aircraft had any corrosion at that time. Palliative action was difficult because of the extent of corrosion and really what was needed was a redesign of the part to eliminate the severe galvanic couple.

Plugs, sockets, terminals, switches have often shown corrosion in Service, sometimes to the extent of permitting tracking. A case occurred some time ago of corrosion arising on butt type contacts in a relay which controlled one section of a fuel transfer circuit in a fighter aircraft. There were several instances of failure to transfer and one aircraft loss could conceivably have been due to this cause. The relay was an enclosed type but not fully sealed; under tropical conditions ingress of moisture vapour with subsequent condensation and corrosion occurred, and finally electrical malfunction.

It may well be that corrosion is a greater contributory factor to some electrical or electronic hiccups than is presently realised. For example the degree of attack necessary to materially change contact resistance may be very slight - modern use of precious metal pins, contacts etc., obviously militates against this but not all electrical connections are so made. Alleviation of corrosion on certain older types of open contacts has been achieved under Service conditions by the judicious use of water displacing fluids and these have been particularly valuable in high temperature high humidity situations where superficial corrosion or traces of moisture was sufficient to cause intermittent malfunction. The purists tended to condemn the use of such fluids contending that the residual organic film, albeit thin and physically weak, increased the contact resistance. Compared to a clinically clean contact, new, dry and without tarnish, this is certainly so, but in practical terms the contact resistance was and remained substantially lower than that attributable to a thin layer of corrosion product after a period of exposure to the aggressive environment. Work is in hand in UK to formulate a special fluid for such electrical contact work and this should be completed fairly soon.

Over the years instances have arisen of corrosion in electric cables and at terminal ends associated with the ingress of water by capillarity. The extensive use of sealing materials and water displacing fluids has controlled this to a large degree and present instances are not anywhere as frequent as previously.

One aspect of 'sealed' equipment in which corrosion has played a part has been in major items which for some reason (not necessarily corrosion) have become unserviceable in use and after opening for examination have been returned through normal logistics channels for repair. The seal being broken, ingress of moisture in the vapour phase has occurred and after receipt at some later (often much later) date in a repair base, corrosion has produced a much deteriorated internal condition. Usually such equipment is not protected on inner components to resist this type of treatment and it is hardly realistic to demand that it should be. On the other hand in an adverse supply situation it may be necessary to attempt in-field rectification if at all possible, and the corrosion implications of doing this need to be well appreciated.

In some items of aircraft safety equipment there have been examples of almost total disregard for the fundamentals of good anti-corrosion practice presumably on the assumption that very detailed, frequent and often protracted in-service maintenance action can be taken - an example is detailed later in the paper on Case Histories. Such instances may require retrospective Service modification action often after costly in-service experience and they exemplify the need for manufacturers of all types of aircraft equipment to study the conditions in detail before finally committing the design.

The field of aircraft equipment is replete with examples of corrosion and corrosion induced cracking, another example to be illustrated concerns the use of a helicopter tail rotor blade with a 'wedge' form root of unprotected stainless steel, fitting into a forged aluminium alloy hub extension arm of 'claw' form. No jointing and no protection existed between the abutting faces and the aircraft regularly operated in a very severe environment. Examples of corrosion at the interface were legion and examples of propagating fatigue cracks from corrosion pits were experienced.

Again in an entirely different context a type of flexible hydraulic hose in the braking system of a fixed wing carrier borne aircraft and a similar hose at a wing fold in another aircraft type were involved in repeated failures due to the fact that the steel braided reinforcing within the hose was covered by an outer covering which was permeable to moisture. Local corrosion of the steel braiding occurred under salt spray contamination and burst hoses resulted with consequent damage and cost. The design involved fairly tight bends and the hose selected was regarded as being the best to fulfil the requirements. In effect the palliative action prior to eventually changing the type of hose was to treat existing new stocks by fitting an outer layer of heat shrinkable neoprene tubing and sealing this to the short metal end sleeves using a co-incidentally heat cured epoxy-phenolic adhesive.

The treatment was entirely successful.

Corrosion Monitoring

Aside from considerations of minimising the effects of corrosion by material selection and enhanced protection, the early identification of the effects of corrosion in Service can be profoundly affected by really efficient corrosion monitoring. Techniques have materially improved over the years, and these cover both amounts of corrosion occurring and also rate of corrosive attack. A review of techniques and applications currently in use has recently been made (15), and areas highlighted where improved methods are desirable. The subject is a wide one and assessments of the cost effectiveness of the more sophisticated methods, and their applicability under operating conditions needs to be made. There is clear indication that improved methods of monitoring in some areas can profitably give earlier warning of the onset of deterioration of corrosion than that obtained by the common use of the Mk I eyeball, although the effectiveness of the latter where it can be applied should not be underestimated particularly when backed with knowledge and experience.

CONCLUSION - BRIEF THOUGHTS ON THE WAY AHEAD

Although this paper has been concerned with past problems and existing deficiencies it is right to state that at present there seems to be a growing appreciation in many quarters of the need to deal with the corrosion problem with much more determination than hitherto. In this respect user experience is dictating increased pressure by procurement agencies on suppliers, and within some manufacturers there is very clear anxiety and effort to attack the problem anew. However there still remains much to be done, and a relatively higher priority for anti-corrosion performance in the design considerations of new equipment could profitably be afforded than has sometimes applied in the past.

In UK we have very recently rewritten the section of the basic design requirement manual for aircraft which deals with corrosion prevention (16), and in the opinion of the author this needs to be implemented with the utmost possible vigour. The whole approach to the problem has to be raised to a new level of awareness and action.

That this is also being done elsewhere is exemplified by the present USAF Corrosion Prevention and Control Programme (17) and it is, I suggest, the professional prerogative of the materials engineer continually to press - sometimes against opposition - in support of the need continually to upgrade the end product. This means in addition to having the right standards defined on paper, the actual achieved quality in line with the design intentions.

Corrosion is everybody's and nobody's business - everyone concerned with design, and production standards is tacitly expected to appreciate the need to apply anti-corrosion measures and to know precisely how to do it to the best effect, but regrettably in some organisations there is no one person or group with a primary responsibility for scrutinising all new designs and projects to see that from the corrosion angle the best possible line of approach has been selected. Training, feed back of information, publicity, are all involved.

For any assurance of success it is necessary to have an integrated Corrosion Control Plan based on a clear objective and involving the actual operating customer (not just the procurement agencies), design, manufacture, quality assurance etc. and this will need to embrace contractual considerations of first costs and their ultimate eventual savings in cost of ownership. Involvement right down the line of main and sub-contractors is essential and the responsibility does not end at the finished part. In-service monitoring both by operator

and manufacturer and an ability and willingness to profit early by any adverse arisings are required.

Finally, corrosion defects are only another factor in the equations concerning reliability and aircraft availability. A recent UK paper by a naval aircraft engineering officer (18) makes the cogent point "it is worth reminding ourselves that both reliability and maintainability can *be the enemies of performance* and that to opt out of the race for performance is a certain recipe for failure especially in a fighting service".

However, improved corrosion prevention is not necessarily synomynous with additional weight or *adverse effect on performance*. What we are striving for is greater criticality in selection of materials and methods in the first place combined with immaculate application of protective techniques at the time of initial build. Only a wholesale involvement of all concerned and a conviction that it is both essential and worthwhile will effect any lasting improvement on the situation.

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CORROSION PREVENTION TECHNIQUES, MAINTENANCE AND REPAIR

by

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SUMMARY

It is shown which possibilities exist to increase the corrosion resistance of aircraft structures, mainly involving aluminium alloys. Considered are: material selection and its treatment, application of suitable surface protections, and appropriate procedures during assembly. Other materials, such as titanium and steel are also taken into consideration. Special attention is drawn to those problems which arise during assembly and result from incompatibility of protective coatings with structural materials or fasteners.

Furthermore, a short description of a procedure is given which is also used to determine inspection intervals taking corrosive influence into account.

As corrosion-preventive coatings on surfaces and fasteners are easily damaged simple and inexpensive repair methods obtain great significance in practice. Finally, it is dealt with methods which are common practice in today's aircraft maintenance to repair or replace corrosion-preventive coatings.

1. INTRODUCTION

In aviation, damage by corrosion is classified as damage that occurs regularly in spite of surface protection. Particularly on aircraft with a long service life corrosion may often necessitate the replacement of structural components the calculated life of which, as based on dynamic stress, for instance has not yet expired.

The frequency of corrosion damage to aircraft may be due to the following facts:

- The customer or user does not always clearly indicate the importance of corrosion prevention. Effective corrosion prevention measures are either given insufficient attention in the development phase or are later deleted for economical considerations, unless increased prevention efforts have been specifically required.

- It is not always possible to predict the degree of corrosiveness that will occur in practical use, because it depends, inter alia, on the maintenance performed.

  A great disadvantage is the fact that it is so far impossible to reasonably simulate long term practical corrosion by short term corrosion tests.

- Suitable design from the corrosion point of view is not always possible.

- Damage to protective coatings during operation cannot be avoided.

The many parameters upon which corrosion processes depend and which are not always fully recognised as well as the above mentioned points show that it will hardly be possible to fully prevent corrosion on aircraft structures. The purpose of this paper, however, is to indicate how corrosion damage can be kept within acceptable limits.

2. CORROSION PREVENTION

The corrosion behaviour of aircraft depends on their structural design as well as their later use and the maintenance conditions. First of all, mention should be made of those aspects and/or measures which are of essential importance from the conclusion of the contract of a project to the end of its development phase. Corrosion preventive measures may be roughly broken down into two groups: corrosion prevention by specification and corrosion prevention by engineering.

2.1 CORROSION PREVENTION BY SPECIFICATION

The initial steps for later avoidance of continual corrosion problems on aircraft structures shall already be taken at the time of awarding of the development contract. It is of great importance that the customer or the future user clearly indicates, in the development contract, the corrosion resistance required for the type of aircraft to be developed, i.e. whether a small or great corrosion prevention effort should be planned for. The customer should also indicate, if possible, the main corrosive environment anticipated for the later use of the aircraft.

MIL-STD-1568 (1) gives an example of how an adequate corrosion resistance could be achieved. In addition to an organization that could be called "Corrosion Management" this standard requires the establishments of a corrosion control plan. It also contains details of protective treatments to be used.

In Germany a specification is being prepared which also describes measures to be taken to ensure the service life of defence material. In this specification life limiting factors are not restricted to dynamic stressing but include also corrosion, ageing and the effect of wear. The need for such a specification resulted from the great number of damages to defence material which had occured during long usage and which had, to some extend, been caused by corrosion, leading to considerable downtimes for maintenance.

It is hoped that such specifications will require corrosion resistance to be made not "as poor as admissible" but "as good as justified in consideration of economical aspects (taking into account maintenance and repair work)".

2.2 CORROSION PREVENTION BY ENGINEERING

Later corrosion behaviour of aircraft structural components, in so far as it can be influenced by design measures, is basically governed by the following factors:

- Selection of proper material and/or use of favourable material combinations
- Appropriate design
- Selection of proper protective treatment

A disadvantage which every engineer in the corrosion prevention field has to accept is the lack of a reasonable method which permits to predict the future in-use corrosion behaviour of components on the basis of short term laboratory tests. Owing to the various parameters by which corrosion processes are affected, the applicability of the test results to realistic environmental conditions is often doubtful. When determining measures of corrosion prevention, it is essential to consider the existing practical experience.

Practical experience is available on, e.g. those points or areas of aircraft structures on which, in general, corrosion is most frequently found (2, 3). These are as follows:

- Engine intakes and cooling air vents
- Landing gear locations and wheels
- Skin seams and fastener holes
- Exhaust areas
- Recesses at folds, flaps and hinges
- Bilges and water entrapment areas
- Battery bays
- Integral fuel tanks

Additional critical areas are rocket and gun blast areas on fighter aircraft and particularly toilet and galley areas on commercial aircraft. Corrosion prevention in these areas requires special attention.

In addition to the special consideration to be given to the structural area affected by corrosion, the type of corrosion is also a major factor for determining any corrosion prevention measures.

The following types of corrosion are generally found on aircraft structures:

TYPES OF CORROSION

Surface corrosion
Crevice corrosion
Dissimilar metal corrosion
Pitting corrosion
Filiform corrosion
Intergranular corrosion
Exfoliation corrosion
Fretting corrosion
Stress corrosion
Corrosion fatigue
Microbiological corrosion

Since the typical appearance of these types of corrosion has been satisfactorily described in the relevant literature, e.g. (2, 3), there is no need for giving details in this paper.

The corrosion behaviour can be influenced by the combined effect of material selection, protective treatment and design, as mentioned above. The aspects to be considered are briefly described in the following sub-paragraphs.

2.2.1 MATERIAL SELECTION

The susceptibility to stress corrosion, exfoliation corrosion, intergranular corrosion, dissimilar metal corrosion, pitting corrosion and surface corrosion can in many cases be reduced by the selection of suitable materials.

Basically, the corrosion resistance of materials should be judged under consideration of the answers to the following questions:

- Which types of corrosion has practical experience shown the material to be susceptible to? What experience has been gained during use?
- What are the possibilities of effectively protecting the material surface from corrosion?
- Is there any incompatibility with other contacting materials?
- Has the current "corrosion prevention to the rules" proved to be adequate?

It should be further borne in mind that the resistance of a material to specific types of corrosion may also depend on the following factors:

- Alloying constituents and heat-treated condition.
- Manufacture of semifinished stock and fabrication of the final part. Manufacturing processes (e.g. heating) could have an essential effect.
- Type, magnitude and direction of stress.

Some hints for the selection of alloys are given in the following sub-paragraphs for the three main structural materials aluminium, titanium and steel used in aircraft manufacture.

2.2.1.1 ALUMINIUM ALLOYS

Aluminium alloys are susceptible to surface, pitting and intergranular corrosion and also to stress corrosion. First three types can, however, be controlled by metal cladding or other protective treatments (see para. 2.2.3). On the other hand, exfoliation corrosion and stress corrosion frequently originate at countersinks and drilled holes, i.e. in places where the protective coating is interrupted. Until recently, particularly the two latter types of corrosion caused difficulties on aluminium alloys of the 7XXX series in the T6 temper, but these have been overcome now by applying different tempers.

With due consideration of all types of corrosion appearing on aluminium alloys and particularly in view of the good resistance of these alloys to exfoliation corrosion or stress corrosion the high strength aluminium alloys shown in table 1 are recommended for use in the tempers specified.

| = Recommended for sheets

▌ = Recommended for plates

O = Recommended for bars and extrusions

* = Recommended for forgings

ALLOY			TEMPER
2124	▌		All artificially aged
2219	| ▌ O	weldable	All artificially aged
2024	| ▌ O		All artificially aged
2014	| ▌ O *		All artificially aged
7075	| ▌ O *		T76XX, T736XX, T73XX
7175	*		T76XX, T736XX, T73XX
7475	| ▌		T76XX, T73XX
7049	*		T76XX, T73XX
7050	▌ *		T76XX, T736XX, T73XX

Table 1 MOST SUITABLE ALUMINIUM ALLOYS FROM THE CORROSION POINT OF VIEW (ESPECIALLY EXFOLITATION CORROSION AND STRESS CORROSION)

It is suggested that these alloys be, in any case, used in the artificially aged temper. Very good resistance to exfoliation and stress corrosion is afforded by the alloys of the 7XXX series in the T73XX temper. This temper is often considered excessively overaged. It is claimed that the stress corrosion resistance requirements had unnecessarily been made too severe resulting in a loss of strength. The current trend is for less overaging, as for instance the 7050 alloy in the T736XX temper.

The 2024 T3 (naturally aged) and 7075 T6 alloys should be mentioned separately. The 2024 T3XX alloy is at present successfully used on a large scale not only for sheets but also for plates and bars on transport and subsonic fighter aircraft. Their corrosion behaviour (particularly intercrystalline and exfoliation corrosion), however, is closely dependent on the quenching rate after solution heat treatment and on intermediate heating to a temperature range between 100° C and 150° C or on heating to temperatures between 170° C and 180° C of insufficient duration.

Plates in the T351 condition have a poorer stress corrosion behaviour in the decisive ST direction than artificially aged plates of comparable thicknesses. Also, too low a cooling rate will increase the susceptibility to exfoliation (this risk exists, e.g. on plates with thicknesses > 50 mm). However, such risk does not exist for sheets. Nevertheless, owing to the negative effect on intercrystalline corrosion behaviour, this alloy should not be used for sheets if heating to the above mentioned temperature ranges may be expected, e.g. during Mach 2 flights or during bonding processes in the manufacture.

The alloys 7079, 7178 and 2020 should not be used anymore. Plates in the 7075 T6 alloy are still being used in some cases for components subjected to pressure (such as the upper surface of the wing). The current trend, however, is to use this alloy for the above mentioned applications in the T76 temper because of its better resistance to exfoliation corrosion.

Metal clad sheets in the 7075 T6 alloy are still being used for the fuselage skin of modern fighter aircraft. There are no objections to their use, provided their thickness does not exceed 2,5 mm.

2.2.1.2 TITANIUM ALLOYS

Owing to their great affinity for oxygen, titanium alloys produce a strongly adhering oxide layer which results in a good overall corrosion resistance of the titanium alloys. Titanium alloys may cause problems by stress corrosion in conjunction with sea water and by hot salt corrosion at temperatures above 250° C. The latter phenomenon is of certain importance in engine manufacture. Table 2 shows the behaviour of various titanium alloys with respect to stress corrosion and hot salt corrosion.

ALLOY	STRESS CORROSION	HOT SALT CORROSION
Ti6Al4V (most important titanium alloy for aircraft structures)	Good	Good up to 300° C
Ti6Al6V2Sn	Good	Poor
IMI 550	Good	Good to fair
Ti4Al3Mo1V	Good	Good
Ti8Al1Mo1V	Bad in thicknesses above 1.5 mm	Poor
Ti5Al2.5 Sn	Good/Fair	Poor

Table 2 STRESS AND HOT SALT CORROSION BEHAVIOUR OF TITANIUM ALLOYS

The titanium alloy Ti6Al4V most widely used on aircraft structures will generally cause no corrosion problems. It does not require protective treatment, not even against microbes, the only exception being fretting corrosion. All titanium alloys are susceptible to this type of corrosion. Suitable preventive measures are described in para 2.2.3.3. Consideration should also be given to difficulties that could arise where titanium alloys are in contact with cadmium and, at higher temperatures, also silver. Titanium components under tensile stress which are in close contact with cadmium plated surface may already crack at slightly increased temperatures (4). The same phenomenon, however, at higher temperatures, will occur in combination with silver. MBB tests (5) have shown the temperature threshold to be between 400° C and 450° C.

2.2.1.3 STEELS

The types of steel generally used in aircraft manufacture are listed in table 3 together with their corrosion behaviour (in an environment as typical for aircrafts). Steels should be selected with due consideration of the susceptibility of certain alloys of specific strength levels to stress corrosion and of their susceptibility to hydrogen embrittlement.

CLASS	ALLOY	GENERAL CORROSION RESISTANCE	STRESS CORROSION RESISTANCE
Low Alloy Steels	4340 HP 9-4-30 H 11 300M	Surface protection required	In general not susceptible with the exception of high strength grades with more than 1500 N/mm^2
Corrosion Resistant Steels			
Austenitic Steels	316	Excellent	Excellent
	347	Excellent	Excellent
	A286	High	Excellent
	321	High	Moderate
	304 (ECL)	Moderate to high	Moderate
	302	Moderate	Low
	303	Low to moderate	Low
Martensitic Steels	440C	Moderate	All grades susceptible to stress corrosion
	420	Low	
	410	to	
	416	moderate	
Precipitation Hardening Steels	PH13-8Mo	High	Susceptibility varies significantly with composition, heat treatment and shape of product.
	PH15-7Mo	High	
	PH14-8Mo	High	
	PH17-4PH	High	
	PH15-5PH	High	
	AM 355	High	
	AM 350	High	

Table 3 CORROSION BEHAVIOUR OF STEELS

MBB have performed special tests on steels HP 9-4-30 and PH13-8Mo. (6,7)

In alternate immersion tests the steel HP 9-4-30 with a strength of 1550 N/mm^2 and without surface protection showed no susceptibility to stress corrosion.

Likewise insusceptible to stress corrosion was the PH13-8Mo steel in the H950 temper. The tests performed on this material were alternate immersion tests with specimens in contact with aluminium half shells and immerged in a 3.5 % sodium chloride solution (7). With prestressing to 0.90 σ_{ty}, the majority of the ruptures occured after more than 1500 hours. Only some few specimens failed between 700 and 1000 hours. The tests also covered the influence of aluminium coatings, such as SERMETEL W, HIGHCOTE 2, which were found to have a fairly good effect.

These tests did not confirm existing test reports on bolts which, clamped between aluminium spacers, had failed in a sodium chloride swab test after a few hours. This result was explained as being due to hydrogen embrittlement.

2.2.1.4 MAGNESIUM ALLOYS

Magnesium alloys are extremely susceptible to corrosion. If at all used with the customer's special agreement, these alloys should be restricted to areas where the risk of corrosion is expected to be low. They should not be used for primary structures or in areas subjected to high wear.

2.2.1.5 NON-METALS

Non metallic materials used shall be moisture and fungus resistent, unless they are hermetically sealed to their environment. The endeavour shall always be to use materials with a low moisture absorption. Plastics, such as polyvinyl chloride, which liberate corrosive vapours already at room temperature or at higher temperatures, should not be used. Such vapours may attack plastics and elastomers as in the case of PVC, but also metals.

Materials, such as PTFE, polyamides, polyurethanes, polycarbonates, polyethylenes, polyalkenes, polyolefins, polysulfones and silicones – just to mention a few – meet these requirements and may be used.

2.2.2 DESIGN PRINCIPLES

Even with properly selected materials and protective treatments, corrosion behaviour largely depends on design details. Susceptibility to stress corrosion, dissimilar metal corrosion, crevice corrosion, surface corrosion, and microbiological corrosion can, to a great extent be controlled by appropriate design.

The following basic points should be observed:

- Access shall be provided to areas which are highly susceptible to corrosion to enable early detection of corrosion damage.

- Aircraft structures shall be sealed to prevent ingress of water.

- Provisions shall be made for adequate venting to prevent trapping and/or accumulation of moisture.

- Care shall be taken to avoid areas in the structure and tanks in which water could accumulate. Condensation areas shall be suitably isolated. Drain holes shall be provided, if necessary. Sharp corners, recesses and crevices shall be avoided so that moisture and solid matter cannot accumulate to initiate local attack. Particular attention shall be given to pipe joints to ensure smooth and uninterrupted contours. If possible, pipes shall be routed to avoid the accumulation of condensation water. Gaps shall be sealed or otherwise protected, if necessary (see para. 2.2.3.4). Sealed floors with suitable drainage shall be provided for galleys, toilets and cockpits. Plastic pipes are most suitable for use as drainage pipes in galleys and toilets.

- Faying surfaces of riveted, bolted or spot welded joints and the attaching and connected parts shall be protected by suitable intermediate layers.

  Paste-like bonding agents used as intermediate layers of riveted joints to improve their dynamic strength have caused corrosion problems due to the absorption of moisture by the bonder. This method should, therefore, be used with caution.

- When used in contact with metals, plastics with a high degree of water absorption, such as foam plastics with open pores, should be sealed, if possible.

- Since the direction in which stress corrosion is most likely to develop relative to the grain flow of the component is ST, any permanent tensional stresses, such as residual stress, in this direction should be avoided. Assembly stresses shall be kept to a minimum by suitable assembly methods, e.g. by using shims. Wherever possible, aluminium alloys should be used in the stretch stress-relieved or compression stress-relieved condition.

  Contours of forgings shall be so designed as to ensure a grain flow appropriate to the direction of stress.

- Contact between dissimilar metals should be avoided wherever possible. Informations about the compatibility of various metals is given in the literature e.g. (2). Where contact between dissimilar metals cannot be avoided owing to specific design requirements, the contact surfaces should be protected by a suitable protective treatment or an intermediate layer, such as a sealant or corrosion inhibiting paint.

  Where contact corrosion is expected to occur, attention shall be paid to the anode to cathode area ratio. Generally, it is advisable to use large anode areas relative to the cathode areas.

- Where painting is used, it should be borne in mind that the paint coating is thinner over sharp edges, thus providing poorer protection.

For better understanding, fig. 1 contains some examples of the above mentioned design principles, taken from the literature (2,3).

2.2.3 SURFACE TREATMENT

Almost all types of corrosion can be controlled with varying results by the selection of a suitable surface treatment. The protective treatments to be applied to aircraft structures are normally established in protective treatment lists applicable to a specific type of aircraft or in company design manuals.

It is important to know the answers to the following questions:

- Is the protective treatment resistent to all operating conditions?

- What experience has been gained with specific surface protections under similar conditions?

- Is the protective treatment compatible with the base material or has the protective treatment any negative effect on component strength (e.g. reduced dynamic strength)? Will the base material be affected when applying the surface protection?

- Is the protective treatment compatible with the material of components which are contacted?

- What is the cost of the protective treatment?

Metal coatings should, if possible, be less noble than the base material to be protected.

Following is a short description of the main protective treatment methods commonly used in current aircraft construction. Emphasis has been given to the problems involved in the combination of various metals.

2.2.3.1 BASIC TREATMENT

2.2.3.1.1 ALUMINIUM ALLOYS

Aluminium sheets used for internal and external aircraft structures should be metal clad. Apart from later painting, Alodine is considered an adequate additional protective treatment. In highly corrosive areas surface protection may be improved by using chromic acid anodization in lieu of Alodine. Non-metal-clad sheets or metal clad sheets with chemically milled areas, forgings and integrally machined parts should be anodized whenever possible.

Anodizing normally reduces the dynamic strength of components. Opinions in other publications as to the amount of reduction relative to untreated or Alodine treated material and the answer to the question of whether sulphuric acid anodization is more unfavourable than chromic acid oxidation are very contradicting. Nevertheless, it would appear advisable to wet blast the parts before anodizing.

One of the disadvantages of anodizing over Alodine treatment is, however, the cost, which is six times the cost of Alodine. This high cost is partly compensated for by the fact that cracks become visible after anodizing, thus avoiding penetrant crack testing of the finished part. A further advantage is the conspicuousness of soft spots which could readily arise by overheating of tool penetration areas during NC machining of aluminium components.

2.2.3.1.2 STEELS

The standard protective treatment for low alloy steels is cadmium plating. According to the latest AICMA specifications, in Europe steels with a strength greater than 1450 N/mm^2 are vacuum cadmium plated to prevent hydrogen embrittlement, whereas in the USA, high strength steels in the 1800 N/mm^2 strength level are still cadmium plated in baths with a low hydrogen content and then degased.

Phosphate layers are primarily lubricant carriers. Although soaked with anti-corrosion oils they only afford conditional corrosion protection.

Corrosion resistant steels, except the 400 series, are normally not given a protective treatment or they are only passivated. Welded parts should generally be passivated.

Other coatings of steels, such aschromium, nickel or other layers are mostly applied to reduce wear.

Hence, low alloy steels are only protected by such layers as long as these are undamaged. Any damage to the layer will result in increased attack of the base material.

In addition, chromium layers strongly reduce the dynamic strength and may cause hydrogen embrittlement when being applied. Therefore, the components shall be shotpeened prior to chromium plating and degased in a vacuum for approximately 24 hours at 180°C after chromium plating. Electroless applied Nickel layers and particularly sprayed on coatings (e.g. zinc) shall be of sufficient thickness (i.e. 20 – 30 μm) to prevent porosity.

2.2.3.1.3 TITANIUM ALLOYS

Titanium alloys do not require protective treatment against electrolytic corrosion and fungal attack at the temperatures prevailing in the structures of today's aircraft.

However, preventive steps have to be taken against fretting corrosion. Silver, which strongly adheres to titanium surfaces when vacuum deposited on intermediate layers, has proved to be very suitable for this purpose.

2.2.3.1.4 BONDED PARTS

Sandwhich components with aluminium honeycomb cores (aluminium honeycombs should be conversion coated) and e.g. less than three glass fibre reinforced epoxy prepreg layers should be sealed with Tedlar foil. Where several layers of foil are used adequate painting may, for example, consist of epoxy primer plus surface lacquer. For corrosion reasons, it would be better to use NOMEX honeycombs in combination with fibre reinforced epoxy skins. According to MIL-STD-1568, metal-clad aluminium sheets shall not be bonded. This restriction is not applicable in Europe because no unfavourable experience has been made in bonding metal clad sheets. Pretreatment consists in pickling only or in anodizing and subsequent application of primer. If only part of the surface of a sheet is bonded, it is usually more economical to spray the bonding primer on the entire sheet. Unbonded areas are then painted. Where primers are used which dry at temperatures lower than the bonding temperature, it shall be checked, if the primer on the unbonded surface softens during the actual bonding cycle, which may cause it to stick to the covering foil.

Bonding seams in water condensation areas or other corrosive areas have previously in many cases been sealed, e.g. with polysulphide sealants and frequently covered with a NIKOTE film to protect them against SKYDROL. Recent weathering tests performed in Guadeloupe in connection with the AIRBUS project, for which great efforts were made on surface protection, proved that bondings whose seams had been sealed with polysulphide sealants, showed a poorer behaviour than the unsealed ones. It is recommended that further tests should be done on this subject.

2.2.3.2 PAINTING

Most aluminium and steel parts are painted with a zinc chromate pigmented epoxy primer in addition to their basic treatment. The inside of aluminium tanks is coated with a anti-fungicide polyurethane paint. Component surfaces belonging to the aircraft internal structure will not receive any further coat of paint. The external structure and also such areas as the undercarriage bay as well as the auxiliary power unit compartment are given an additional coating of surface lacquer. For military aircraft polyurethane lacquers are specified in most cases. These lacquers can only be removed with a paint remover. Where frequent removal of the surface lacquer is anticipated, it is recommended to use acrylic resin based surface lacquers.

The use of an opoxy primer plus polyurethane surface lacquer system which was used in Germany, for example on PHANTOM aircraft, did not yield good results.

The paint peeled off in areas exposed to elevated temperatures, e.g. during Mach 2 flights. Painting tests performed on the F-104 showed similar results. Modified polyurethane surface lacquers from various suppliers are again being tested on an F-104 aircraft. The results are still outstanding.

2.2.3.3 SPECIAL TREATMENTS

The stress corrosion, corrosion fatigue, and fretting corrosion behaviour can effectively be improved by inducing residual compression stresses through cold working of the surfaces. Residual compression stresses may be induced, e.g. by rolling or shot-peening. The behaviour of high strength bolts, particularly when prestressed, can be improved significantly when rolling also the shank in addition to thread and fillet (9). Bolts in H 11 with a strength of 1800 N/mm^2 treated as above were successfully used on the TRANSALL, whereas bolts with a ground shank (standard manufacturing method) failed due to stress corrosion. Non-corrosion resistant steel bolts are usually cadmium plated and then in most cases are given a dry lubricant coating as in the case of passivated corrosion resistant steel bolts and anodized titanium bolts. It may be pointed out that dry lubricants on an MoS_2 basis are hygroscopic. Moisture absorption is, however, greatly reduced by the use of MoS_2 epoxy paints.

Silver coating and shot peening may effectively prevent fretting. In many cases, plane contact surfaces may be protected with epoxy primer. A sealant may, in addition, be applied to the contact surfaces, if required.

2.2.3.4 ASSEMBLY AND RELATED PROBLEMS

The corrosion behaviour is essentially improved by wet assembly of the structure. Chromate pigmented epoxy primers or acrylic resin based paints and sealants may be used for this purpose. The MBB procedure is as follows:

- All faying surfaces are wet assembled with a chromate pigmented acrylic resin based paint. In the undercarriage bay and in areas where sealing is required anyhow, a sealant is used.

- With the exception of universal head rivets in through holes in non-corrosive locations of the internal structure, rivets and Hi-Loks are also wet assembled in accordance with the above statement. Hi-Loks with underhead sealant, which have been newly offered, need not be wet assembled either and appear to be cost effective.

- Bolts, corrosion resistant steel bushes, cadmium plated steel and non-ferrous metal (copper basis) bushes and bearings in aluminium structures are wet assembled using paint. Where these are installed in a corrosive environment they are also sealed. Corrosion resistant steel bushes and bolts used in such areas should be cadmium plated.

Difficulties may arise were steel bolts are to be installed in aluminium or titanium structures. Although cadmium plated steel bolts are compatible with aluminium with respect to contact corrosion, they should not be used in titanium structures. Corrosion resistant steel may be well combined with titanium but may cause contact corrosion when used in aluminium. Nevertheless, the use of corrosion resistant steel bolts is generally recommended for the above applications. However, the bolts shall be wet assembled and sealed, if required.

Monel rivets could cause similar problems. They should be cadmium plated for installation in aluminium structure. However, their compatibility with titanium structure is better, if they are non-cadmium plated. In special cases steel bolts or monel rivets with an aluminium coating, such as Sermetel W, should be used for such applications.

Since titanium has a corrosion behaviour against aluminium similar to that of corrosion resistant steel, it is recommended that titanium fasteners in aluminium structure should at any rate, be wet assembled and, where subjected to severe corrosive conditions, provided with an aluminium coating.

A promising procedure for electrolytic aluminium deposition is the so-called SIEMENS method (10). With this method aluminium is precipitated from organic compounds without producing hydrogen. This method is, therefore, most suitable for the coating of high-strength steels and could, possibly in the future, replace cadmium plating.

3. MAINTENANCE

Chief maintenance activities for the prevention of corrosion and/or major consequential damage during use are as follows:

- Periodic removal of corrosive media and maintaining of an intact surface protection.
- Protection of parked aircraft against the ingress of corrosive media.
- Periodic inspection of aircraft for corroded spots.
- Recording of corrosion damage by each Air Force wing and, if necessary and advisable, statistical evaluation of frequency and beginning of corrosion.

The maintenance personnel shall be instructed not to damage the existing surface protection during maintenance work on the aircraft.

3.1. PROTECTION OF PARKED AIRCRAFT

On parked aircraft, sensitive parts and openings shall be covered to protect them from moisture, dirt, sand, salt etc. However, after aircraft have been in a moist environment the covers should be removed from the openings as soon as the environmental conditions permit in order to allow adequate venting.

3.2. CLEANING OF AIRCRAFT

After off-shore or shooting missions, the aircraft should be cleaned or washed, if possible after each flight, to remove corrosive media. The aircraft should also be thoroughly cleaned before every inspection. Regular cleaning with water to remove any residual salt has a very good effect. Foam, steam or special cleaners may be used to remove persistent dirt or grease. Where chemicals are used, it shall be ensured that they have no detrimental effect on materials they get in tough with, such as damage to plexiglas, softening of paint etc. During each cleaning, a check should be made, as far as feasible, to ensure that vent and drain holes are not clogged. It is often advisable to apply an additional temporary surface protection, such as chromate pigmented lanolin, to areas of the internal structure which are exposed to corrosion or where the surface protection has been damaged.

3.3. INSPECTION

Unlike crack inspection intervals, corrosion inspection intervals cannot be established by analytical methods. The maintenance personnel shall, therefore, be instructed to constantly look for corrosion damage. Everybody should be obliged to report any corrosion damage detected.

In addition, assemblies, joints or parts classified as problematic from a corrosion point of view, shall be identified and included in the inspection schedule for periodic inspections and/or modification overhauls. Inspection intervals which have been analytically derived solely from fracture mechanics considerations, should be appropriately reduced, if the part concerned may develop corrosion. MBB have developed an analytical method for the determination of inspection intervals with consideration of corrosive effects, which is, for example, based on the Maintenance System Guide (MSG) procedure (11). Fig. 2 shows the pattern to be used and an evaluation form. The corrosion ratings shown in the corrosion block are defined in a separate document depending on material and protective treatment.

Corrosion damage may be detected mainly by visual inspection using such aids as intrascopes, mirrors etc., for places with difficult access. Surface corrosion can be directly recognized, whereas interface corrosion or exfoliation can be recognized by slight bulges in the surface or spread joints. Such phenomena indicate advanced corrosion and require further steps, such as removal of the protective coating etc. Non-destructive test methods, such as penetrant, magnetic particle flaw detection, X-ray, eddy current and ultrasonic methods, may only be conditionally used to detect corrosion damage. Their application has to be decided from case to case. Ultrasonic, X-ray and eddy current tests (e.g. for holes) could be used for corrosion detection in blind but accessible places, provided the critical area is known. Penetrant and magnetic particle flaw detection tests (the latter being only suitable for magnetic material) may be used to detect stress corrosion cracking or to confirm freedom from cracking after removal of the corrosion products.

Visual inspection of the entire airframe for corrosion and, in particular, periodic inspection of areas strongly exposed to corrosive attacks are regarded as routine inspections.

Special local inspections of structural parts with difficult access shall be carried out on the occasion of other work for which covers and panels have to be removed. During such inspections particular attention should be paid to areas where moisture could accumulate or be trapped for a fairly long time,

for example in sound proofing material generally installed between the skin and the inner panels, which could be slightly moistened by condensed water. Blind places or places with difficult access should be either avoided or given special corrosion protection. Nevertheless, if such places require inspection, it would be recommended that spot checks should be carried out, and the results of these checks should be used to assess the condition of the whole fleet.

It is generally recommended that all serious corrosion damage discovered should be recorded stating any repair steps taken, and statistically evaluated to determine their frequency and the time they took to develop. This yields valuable experience for future practice and gives detailed information on the life of repairs.

4. REPAIR

Damage caused through corrosion is generally repaired as follows:

- Remove paint
- Remove corrosion products
- Check if the component may be further used after additional repairs
- Apply surface protection

4.1. PAINT REMOVAL

To remove the paint, suitable solvents or paint removers shall be selected. All seams, joints, skin overlaps, inspection areas, inspection holes, bonding seams as well as rubber and plastic parts shall be masked. After removal of the paint any remnants have to be washed off or removed otherwise.

4.2 CORROSION REMOVAL

Corrosion products may be removed mechanically or chemically, considering the following points:

- Corrosion has to be removed completely.
  If necessary, complete removal has to be proved by non-destructive test (NDT) methods.
- After corrosion removal there shall be no stress raisers.
- The surface cleaned of corrosion shall not contain any remnants of the tools or agents used for corrosion removal.
- Any existing cracks shall not be smeared up. Smearing can be avoided by vacublasting after visible corrosion products have been ground off.
- The base material exposed shall not sustain any metallurgical damage or damage by heating.

Corrosion products, particularly on aluminium, are mechanically removed with scrapers, flexible grinding disks or sand paper and glass bead peening.

Chemical methods are frequently used for steel (e.g. phosphoric acid). Their advantage is that they permit easy treatment of large areas and areas of complicated shape. It should, however, be borne in mind that chemical milling should not be used for steels with a strength $> 1250\ N/mm^2$ due to the risk of hydrogen embrittlement. The chemicals used shall be prevented from penetrating into gaps. After completion of the treatment the areas involved shall be cleaned with water.

4.3. LIMITS OF REMOVAL

For strength reasons corrosion products may only be removed to certain limits, which shall be established by the stress department and incorporated in repair manuals. Normally these limits are given as a percentage wall thickness or percentage flange height. Their amount is within the standard wall thickness tolerances and in many instances, it is more than those figures. Sheets often have limits of 10 % of the wall thickness and machined parts 5 %. When corrosion is removed from edges, holes shall retain a minimum edge distance of 2 x d (d = diameter). In addition, information shall be provided as to what maximum percentage of a surface area and what percentage of the number of holes in a row may be repaired by corrosion removal within the limits specified. Holes may be repaired by boring to the first oversize. Corrosion affected fasteners shall not be repaired and must be replaced.

Before a new surface protection is applied after repair, the permissibility of the repair shall be verified. In special cases or where the limits specified for corrosion removal have to be exceeded, the stress department shall be consulted. If necessary, a special repair may be agreed upon depending on the cost and the delivery situation, or the part has to be disposed of.

4.4 RESTORATION OF SURFACE PROTECTION

After the surface has been cleaned and/or degreased with suitable agents (alkaline degreasing agents should not be used on aluminium structures) the specified protective treatment consisting again of basic treatment (not for small scratches) plus painting may be applied. In many cases a primer, such as a wash primer, is used in lieu of the basic treatment. Basic treatment of aluminium alloys often consists of brushable Alodine, whereas a cadmium brush coating is applied to steels up to medium strength. Before any of the two procedures is applied directly to the structure, seams and gaps shall be sealed.

The paint system then applied shall be identical with the one of the surrounding structure.

5. FINAL REMARK

This paper was intended to give a survey of measures currently taken in the design and maintenance of aircraft structures, and actions which will be recommended for the future. Owing to the complexity of the subject many points could only be touched. Especially the great number of accessory materials, cleaning agents etc. available for maintenance, their specific use from a material point of view and their compatibility with structural materials could not be discussed here.

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(5) MBB Bericht FE 217/STR-P-0001, März 1975, Zeitstand und Ermüdungsversuche an Proben der Legierung Ti 6 Al4V in Kontakt mit Silber.

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(7) MBB Bericht M/FE 2170/1257, September 1974, Spannungsrißkorrosionsversuche am Werkstoff PH 13-8Mo mit unterschiedlich bearbeiteten Oberflächen, mit und ohne Oberflächenschutz.

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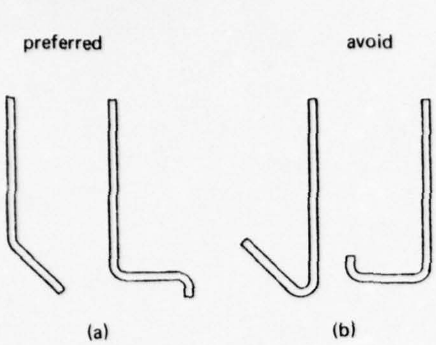
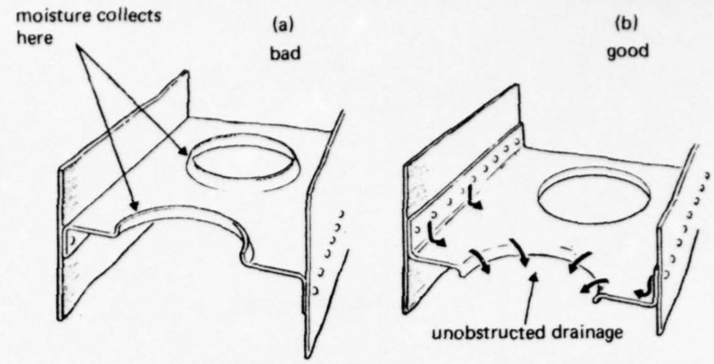
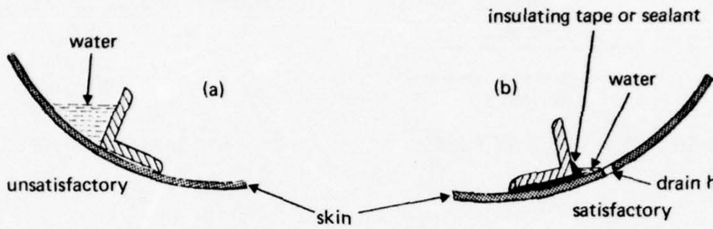
(11) L. Granquist: Interpretation of Maintenance System Guide, ASD Inter-Office Memo, MR/0255/MB/LG/cf, 4th Oct. 72.



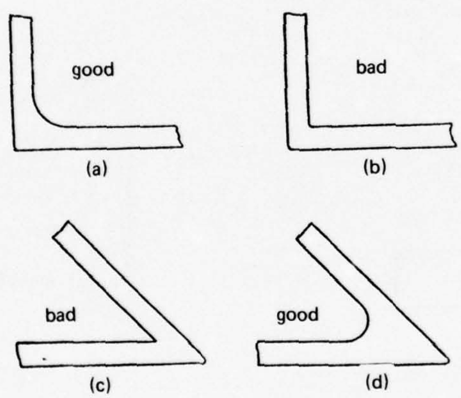
A) FLANGE DESIGN



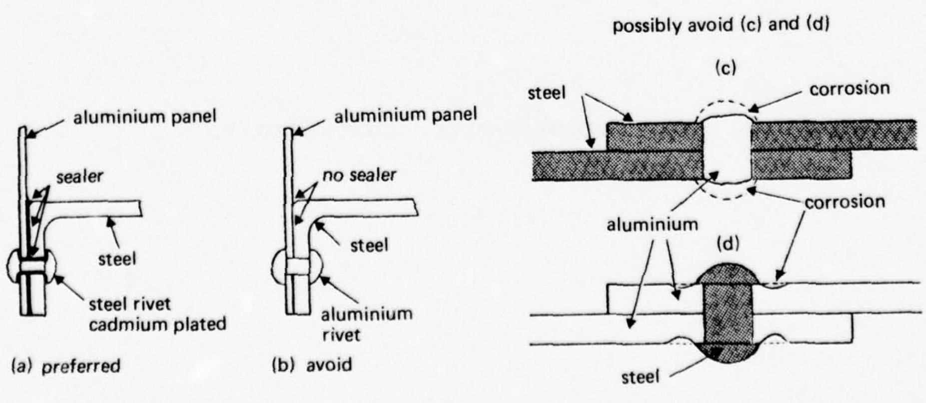
B) LIGHTENING HOLES IN HORIZONTAL DIAPHRAGMS



C) WATER TRAPS AND FAYING SURFACES

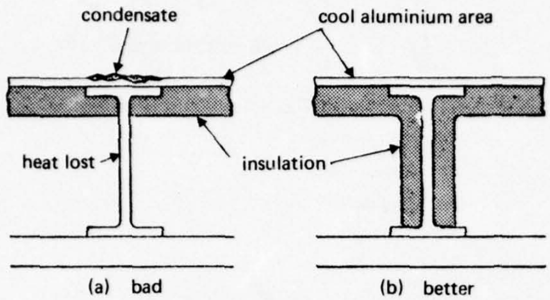


D) DESIGN FOR EASY CLEANING

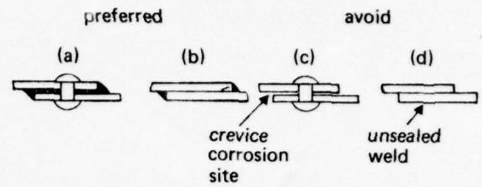


E) DISSIMILAR METALL CORROSION

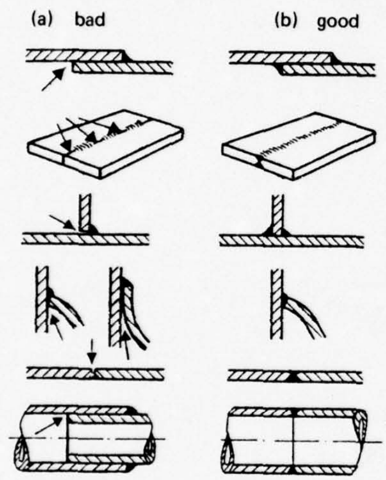
Fig. 1 SOME DESIGN EXAMPLES, ACCORDING TO [2], [3]



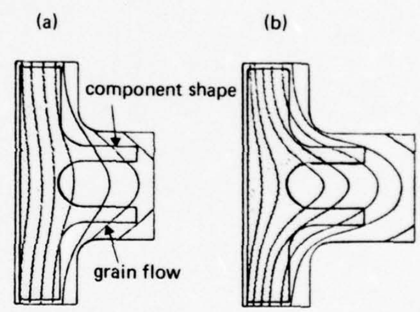
F) PREVENTING CONDENSATION ON STRUCTURES



G) SEALING OF A BUTT JOINT



H) DESIGN OF WELDED PARTS



I) IMPROVING GRAIN FLOW

Fig. 1 SOME DESIGN EXAMPLES, ACCORDING TO [2], [3]

NOMENCLATURE:	TORNADO SSI ANALYSIS SHEET	NAME:	ISSUE:
APPLICABILITY:		FIRM:	WUC:
		DATE:	

LOCATION: DWG NO.:	DESCRIPTION:
REASON FOR SELECTION:	
REFERENCES:	
MATERIAL SPEC.: PAN:	SCHEMATIC:
CORROSION PROTECTION:	
CALCULATED FATIGUE LIFE (FH) (INCLUDES APPROPRIATE SCATTER FACTOR)	
FRACTURE MECHANICS CALCULATION:	
INITIAL CRACK LENGTH: CRITICAL CRACK LENGTH:	
CRACK TYPE: SAFE CRACK GROWTH LIFE:* FH	
FRACTURE MECHANICS TEST: TYPE OF TEST:	
ARTIFICIAL CRACK? INITIAL LENGTH:	
ACHIEVED LENGTH: SAFE CRACK GROWTH LIFE:* FH	
RATING SUMMARY	

RATING FACTOR	RATING	REMARKS
MATERIAL/PROT./COMB.		
STRESS CORROSION		
ENVIRONMENT		
CORROSION (OVERALL)		
FRACTURE MECHANICS		
COMBINED RATING		

RECOMMENDED INSPECTION INTERVAL:	
IS EXTERNAL DETECTION OF DEFECT POSSIBLE?	
ACCESS PROCEDURE:	
RECOMMENDED INSPECTION METHOD:	REMARKS: * – SCATTER FACTOR OF TWO INCLUDED.
APPLICABLE MAGERD(S):	

PANAVIA FORM 20048 (Rev. 15. 7. 1976)

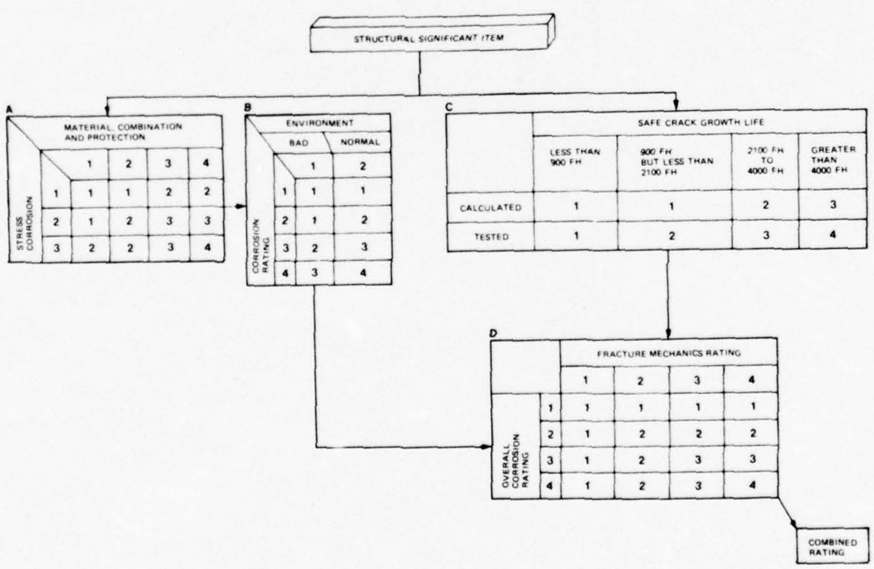


Fig. 2 SCHEMA FOR DETERMINATION OF INSPECTION INTERVALLS BASED ON MSG [11]

LA CORROSION - ETUDE ET DETECTION

par

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RESUME

Pour l'étude des phénomènes de corrosion, deux voies d'approche sont explorées parallèlement : les essais de reproduction et d'accélération de la corrosion - la détermination des vitesses de corrosion.

Essais accélérés

Divers types d'essais ont été développés pour reproduire et accélérer les phénomènes naturels. En Aéronautique, par exemple, on utilise les essais de brouillard salin, les immersions continues et alternées, les cyclages climatiques, les expositions marines et tropicales.En fait ces types d'essais sont toujours adaptés en fonction du problème posé. On montrera à partir d'exemples comment ont été conduites la mise au point et l'exploitation de ces essais.

Mesure des vitesses de corrosion

La vitesse de corrosion constitue bien évidemment un outil précieux de prévision des dégâts dûs à la corrosion et c'est ce qui justifie l'intérêt de sa mesure. On décrira les moyens utilisés dans ce sens par le LABORATOIRE CENTRAL de l'AEROSPATIALE, en particulier l'utilisation des courbes potentiostatiques et des mesures d'impédance faradique à faible fréquence. L'application de ces méthodes au contrôle de l'anodisation montrera l'avantage de telles méthodes. Dans le cadre de la corrosion sous tension, l'étude de la cinétique de propagation des criques sera de même un puissant moyen d'investigation et de prévision.

Moyens de détection

Si les examens visuels sont le plus souvent révélateurs, l'utilisation de méthodes de contrôle non destructif telles que radiographie, ultrasons, holographie, courants de Foucault ... sera très profitable.

A partir de cas pratiques rencontrés en Aéronautique (corrosion intercristalline et corrosion sous tension des alliages d'aluminium, corrosion en milieu confiné des structures en nids d'abeilles, corrosion filiforme sous les peintures ...) l'exposé montrera les possibilités et les limites des méthodes d'étude et de détection de la corrosion.

I - INTRODUCTION

Dans de nombreuses branches industrielles, on a maintenant pris conscience des frais importants occasionnés par la corrosion et la réparation des dégâts qui lui sont imputables. A titre d'exemple, citons qu'en 1968 le coût de la corrosion en Allemagne a été évalué à 9 milliards de dollars. On a estimé qu'au moins 3 milliards auraient pu être économisés par des solutions mieux adaptées. Ainsi, les Laboratoires de Recherches ont été conduits à se préoccuper de plus en plus de la compréhension et de la prévision de ce phénomène qui s'est avéré ruineux, avec, en plus, dans l'Industrie Aéronautique, le risque d'avoir des conséquences sur la sécurité des passagers.

Le LABORATOIRE CENTRAL de l'AEROSPATIALE qui, depuis une vingtaine d'années, travaille sur ces problèmes a acquis dans le domaine des essais et des détections de corrosion une vaste expérience,dont nous donnons ici quelques aperçus, essentiellement axée sur les alliages légers, matériaux de base de l'Industrie Aéronautique.

2 - ASPECT THERMODYNAMIQUE ET CINETIQUE

Thermodynamique

Il est possible, théoriquement, de prévoir si une réaction chimique peut ou non se produire; dans le cas de la corrosion en milieu aqueux, la connaissance du diagramme thermodynamique tension - pH (diagramme de POURBAIX) permet de déterminer les possibilités de corrosion.

Par exemple, le diagramme de l'aluminium délimite les domaines de corrosion uniforme et de corrosion par piqûres.

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DIAGRAMME DE POURBAIX

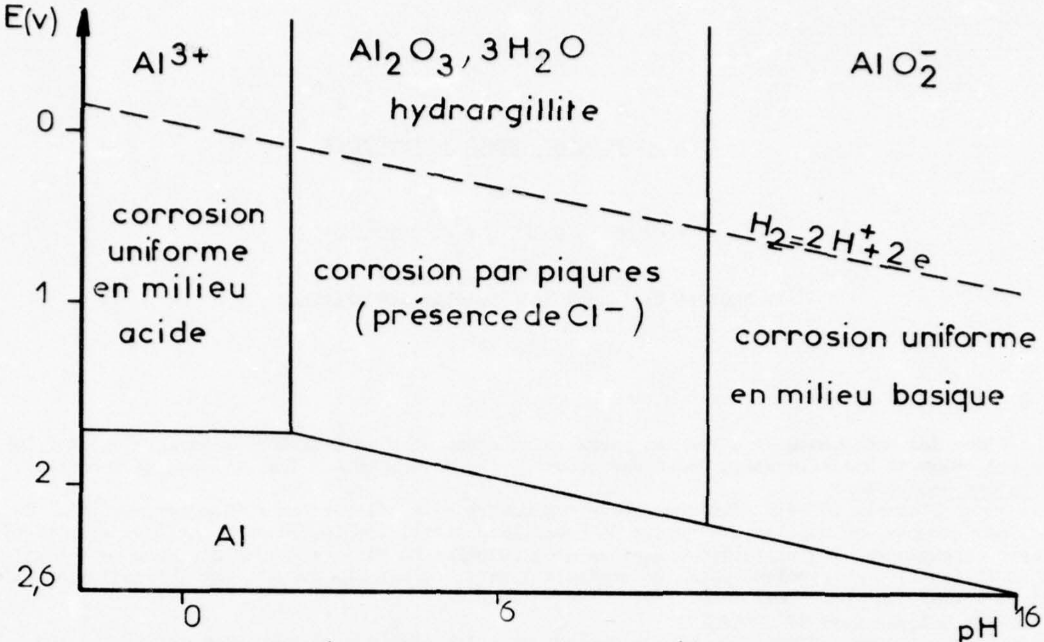


Diagramme d'équilibre Tension-pH Aluminum - Eau 25°C

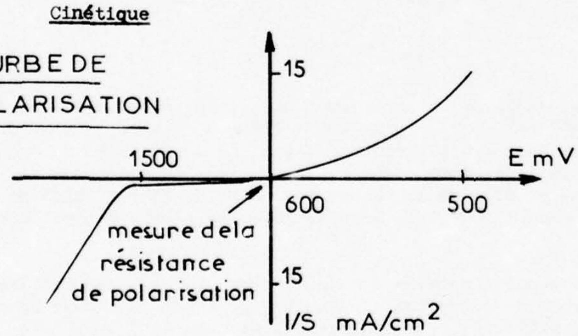
Vers les pH très acides se situe un domaine de corrosion uniforme avec formation d'ion Al^{3+} ; nous citerons les corrosions en milieu confiné par exemple sous les peintures (corrosion filiforme) ou dans les assemblages collés.

Dans un vaste domaine (pH 2 à 10) l'aluminium se recouvre d'une couche passive d'alumine. Les défauts de cette couche protectrice provoquent une corrosion par piqûres. Ce type d'attaque locale est d'ailleurs fréquemment rencontré sur les alliages légers.

A pH basique, on retrouve une corrosion uniforme avec formation d'ion aluminate AlO_2^- ; sur avion, ce type de dégradation est peu courant mais peut se produire au voisinage des accumulateurs.

<u>Cinétique</u>

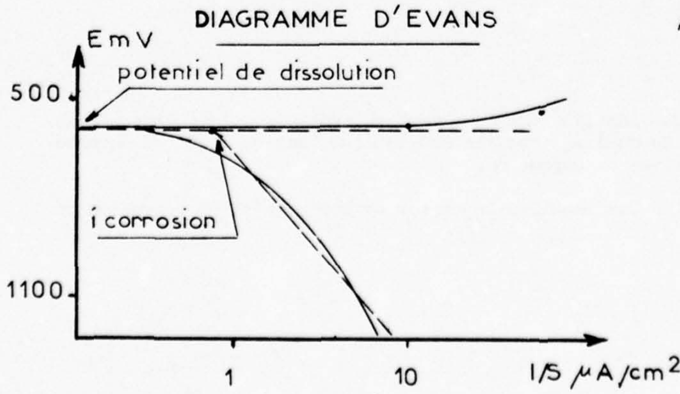
COURBE DE POLARISATION



La cinétique de dégradation à ces divers pH peut être déterminée par des mesures électrochimiques (dans le cas de réactions d'activation).

- Tracé des courbes intensité potentiel, détermination du courant de corrosion par extrapolation des droites de TAFEL (diagramme d'EVANS) ; mesure de la résistance de polarisation inversement proportionnelle dans la plupart des cas au courant de corrosion.

DIAGRAMME D'EVANS



A-U4G1 dans NaCl 3% + $K_2Cr_2O_7$ 5.10^{-3} M

Loi de TAFEL $E = a + b \log i$

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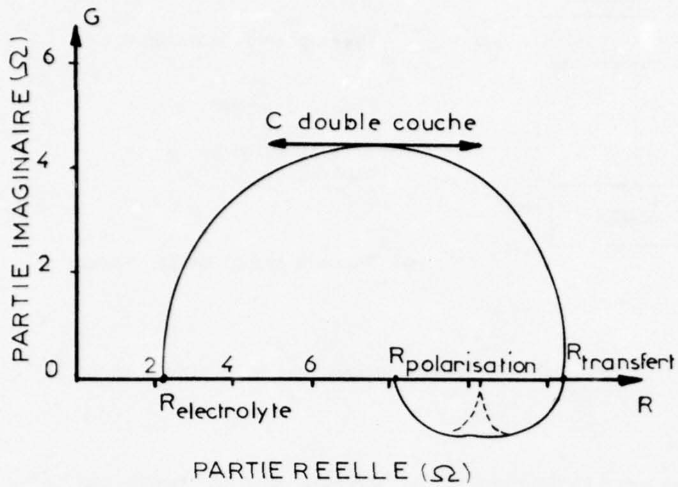
DIAGRAMME D'IMPEDANCE FARADIQUE



Fer Armco en milieu sulfurique d'après I. Epelboin (CNRS)

- Tracé au potentiel de corrosion des diagrammes d'impédance faradique donnant pour des cas simples la résistance de polarisation Rp, la résistance de transfert Rt inversement proportionnelle au courant de corrosion, la capacité de double couche.

Les simples mesures de perte de poids sont souvent une utile indication.

Si ces méthodes s'appliquent pour les corrosions superficielles uniformes elles sont plus difficilement exploitables pour les corrosions localisées.

Nous verrons que d'autres méthodes permettent un suivi de réaction ; ainsi, dans le cas de corrosion sous tension, la cinétique de propagation peut être déterminée par le suivi de la progression de la fissure.

3 - PRINCIPES D'ETUDE DE LA CORROSION

En fait, s'il est possible en général de classer les divers types de corrosion, chaque cas est le plus souvent un cas particulier à étudier comme tel. Deux types de questions peuvent être posés au Laboratoire de Corrosion : 1 - choix d'un nouveau matériau et de sa protection
2 - remède à une dégradation apparue en service.
Dans les deux cas, il est nécessaire de considérer tous les paramètres se rapportant au matériau et au milieu environnant.

Paramètres

Matériau
- composition chimique
- structure métallographique
- état de surface
- forme de la pièce
- contacts avec autres matériaux
- modes d'assemblage
- contraintes (internes et externes) ....

Milieu
- H_2O (humidité ambiante, rétentions, condensations)
- O_2 (aération)
- Ions(chlorures, sulfates, nitrates ...)
- pH
- température ......

L'étude pourra être réalisée suivant deux types de schéma :

Premier cas : choix d'un nouveau matériau et de sa protection

ANALYSE DES PARAMETRES

↓

REALISATION DE TOUS LES TYPES D'ESSAIS NECESSAIRES

↓

DEPOUILLEMENT → MODIFICATION DES PARAMETRES (matériau, protection, milieu) → REALISATION DE TOUS LES TYPES D'ESSAIS NECESSAIRES

↓

CHOIX - Matériau à utiliser dans l'état X dans le milieu Y

../..

Deuxième cas : recherche d'un remède à une corrosion apparue en service

DETECTION DE LA CORROSION

EXPERTISE + ANALYSE DES PARAMETRES

Type de corrosion connu Cinétique inconnue	Type de corrosion connu Cinétique connue	Type de corrosion inconnu
↓	↓	↓
Détermination de la cinétique		Essai de reproduction ↓ Détermination de la cinétique

REMEDE

Arrêt total → Essai de vérification ← Ralentissement de la vitesse

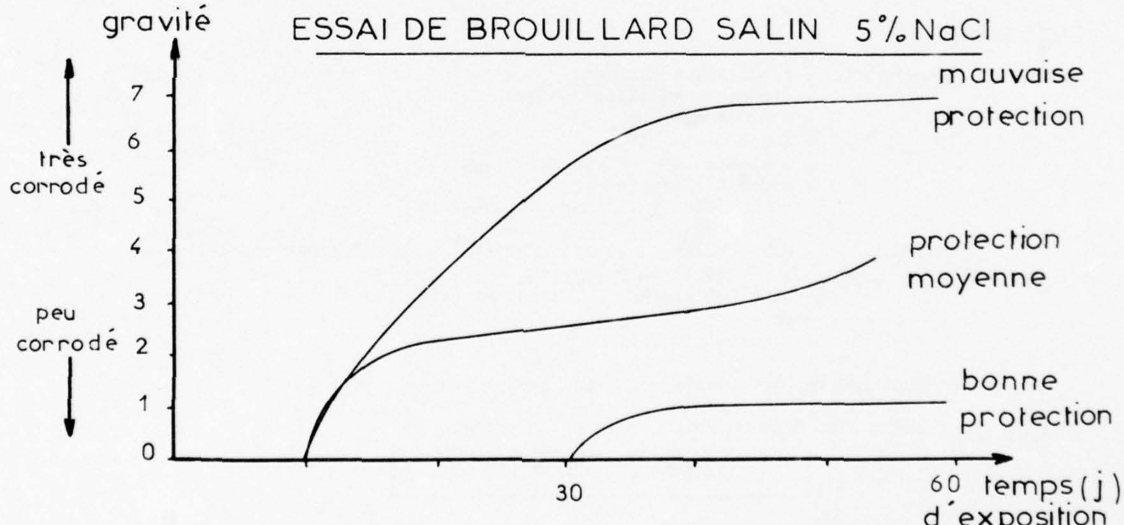
On comprend à la vue de ces schémas très simplifiés, la somme d'essais nécessaires à la prévision et la prévention des corrosions.

4 - LES METHODES D'ESSAIS

Sur avion en service, une quantité importante d'eau de condensation est présente dans la plupart des zones (réservoirs, structures sandwichs, aménagements cabine, cases de train ...). Cette eau, le plus souvent, a un pH variant entre 5 et 9 et contient toujours des chlorures.

4-1 Initiation de la corrosion

Corrosion par piqûres : le milieu ambiant est donc susceptible d'initier une corrosion par rupture de la couche d'alumine passive. Cette initiation peut être reproduite en Laboratoire, par exemple par l'essai bien connu de brouillard salin. Pour notre part, nous utilisons un brouillard salin à pH neutre ayant une concentration de 5% en chlorure de sodium et une température de 35°C. Cet essai est largement utilisé pour le contrôle des protections et des peintures. On relève alors pendant une durée pouvant atteindre 1500 h. la gravité de corrosion en fonction du temps.



A-U4G1 protégé par système de peinture polyuréthane

Corrosion de frottement : dans les assemblages, l'initiation peut être causée non par le milieu ambiant mais par un frottement. Les microdéplacements sous charge entrainent une rupture de la couche passive où se localisera ensuite une propagation par corrosion simple, corrosion sous tension, fatigue ou fatigue-corrosion. Il est possible en Laboratoire de reproduire la corrosion de frottement, par exemple par un essai de fatigue sur assemblage, cet assemblage pouvant être soumis simultanément ou périodiquement à une ambiance corrosive.

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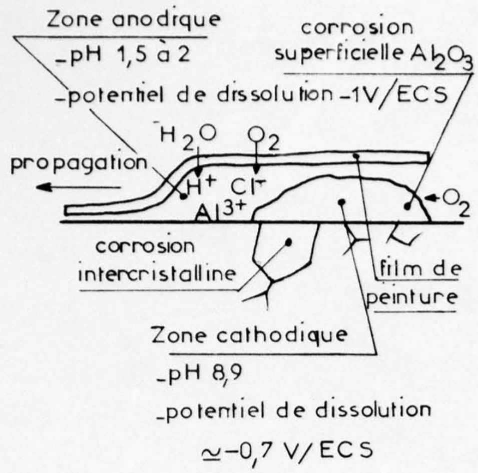
- Principe de la corrosion filiforme d'après AW. Bethune (Boeing)



Corrosion filiforme: si le milieu ambiant a un pH voisin de la neutralité il n'en est pas de même dans les zones confinées (sous les protections par exemple) où, comme nous le verrons plus loin, le pH peut devenir très acide. Nous citerons en exemple la corrosion filiforme qui, sous la forme de " fils " cheminant sous la peinture à partir de discontinuités (rivets, bords des jonctions de fuselage) est une attaque superficielle pouvant être l'initiation par exemple d'une corrosion intercristalline.

Ce phénomène peut être artificiellement reproduit en Laboratoire. L'essai consiste à soumettre une éprouvette peinte, rayée en croix jusqu'au métal, aux vapeurs d'acide chlorhydrique durant 30 minutes et, ensuite, à l'exposer en étuve humide à 40°C et 80% d'humidité relative.

Dans ces conditions pour une protection défaillante, on constate au cours du temps l'apparition et la progression de corrosion filiforme à partir des rayures. Le critère d'acceptation retenu est que les " fils " ne doivent pas dépasser 2 mm après 40 jours d'essai.

Ces exemples mettent en évidence la possibilité en Laboratoire de reproduire des initiations de corrosion.

INITIATION

MILIEU NEUTRE → PIQURES

MECANIQUE (ex fretting) → RUPTURE COUCHE PROTECTRICE

MILIEU ACIDE (ex corrosion filiforme) → DISSOLUTION SUPERFICIELLE

→ PROPAGATION (ou non)

Le dépouillement des essais de corrosion montre que l'initiation est aléatoire et qu'en fait cette phase de corrosion est difficilement prévisible.

4-2 Propagation

La propagation au sein de l'alliage léger peut, quand elle se produit, être soit intercristalline, soit transcristalline. Elle peut être influencée par plusieurs facteurs. Parmi les principaux, nous citerons : les contraintes - le confinement - le couplage avec un matériau différent - la structure métallurgique.

Influence des contraintes : dans ce cas la propagation est une corrosion sous tension inter ou transcristalline. Les méthodes d'essai de C S T n'étant pas normalisées, plusieurs variétés de montage d'éprouvettes et de milieux corrosifs sont utilisées ; les conditions d'essais sont également très diversifiées. Selon BRENNER (1), les essais de corrosion sous tension peuvent être effectués selon deux groupes de procédés : charge imposée constante ou déformation constante. Une importante différence entre ces deux types est que, à charge imposée constante, la contrainte augmente en fonction de l'affaiblissement du matériau alors que, sous déformation constante, la rupture en corrosion sous tension peut ne pas intervenir par suite de phénomène de relaxation des contraintes. Chacune de ces méthodes présente avantages et inconvénients et le choix dépend souvent de multiples raisons : prix de revient - forme du produit - contraintes de service - études fondamentales. C'est ainsi que l'on rencontre plus d'une douzaine de types d'essais faisant appel à la flexion, la traction, contraintes polyaxiales, avec des formes d'échantillons variées, des contraintes élastiques ou (et) plastiques.

L'essai peut être réalisé sur éprouvette lisse ; on englobe ici l'initiation et la propagation ; ou sur éprouvette précriquée pour n'étudier que la propagation.

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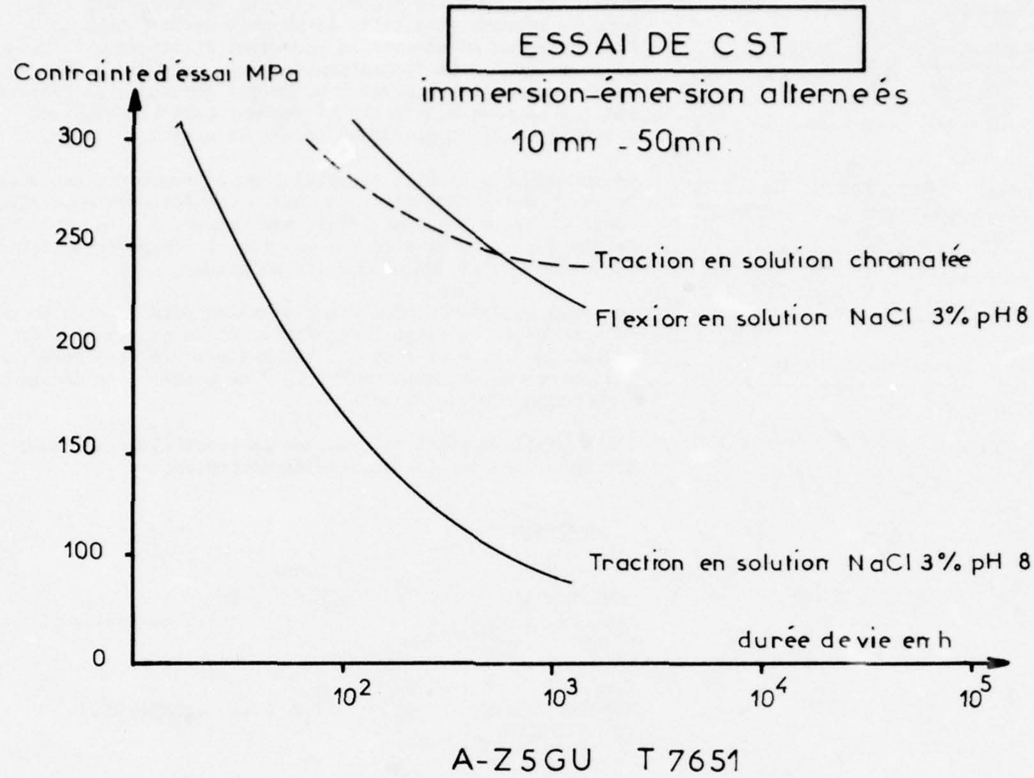
a) <u>essais sur éprouvettes lisses</u>
On trace la courbe de variation de la durée de vie en fonction de la contrainte appliquée.



Comme nous le montrons, cette courbe est fonction du type de sollicitation et du milieu d'essai. Il faut donc choisir arbitrairement la méthode d'essai afin de disposer d'un moyen d'étude comparatif le plus simple et le plus reproductible possible. Suite à une vaste étude à l'échelon français, nous avons choisi les conditions suivantes : (2)

. Les échantillons sont prélevés dans le sens travers court.
. Usinage des échantillons : rugosité inférieure à 0,7 µ C.L.A soit ▽▽
dimensions de la partie calibrée des éprouvettes : ∅ 4 mm l = 25 mm
. Préparation de surface : décapage fluonitrique (Norme AIR 9050 C) = une minute dans la solution à 95°C de NO_3H pur (63%) 50 cc/l + FH pur (60%) 50 cc/l - Rinçage à l'eau - Passivation dans NO_3H pur.
Les échantillons doivent être mis en essai entre 24 et 48 h. après décapage.
. Mise sous tension (5 échantillons pas cas) : tensions recommandées = 75, 50 et 30% de Rp 0,2. La tension est appliquée par un dispositif de flexion à tension constante.
. Milieu corrosif (ASTM G 44-75) : NaCl 3,5% solution préparée à partir d'eau permutée (ρ 1 MΩ) et de réactif pur 6,4 pH 7,2
. Application : immersion (10 minutes) - émersion (50 minutes) 24 h. sur 24 pendant 30 jours.
. Examens micrographiques : ces examens sont destinés à séparer les ruptures mécaniques consécutives à la formation de piqûres, des ruptures de corrosion sous tension.
. Expression des résultats : les durées de vie sont exprimées en jours. On utilisera également le critère :
A pas de rupture à 75% Rp 0,2
B rupture à 75% - pas de rupture à 50% Rp 0,2
C rupture à 50% - pas de rupture à 30% Rp 0,2
D rupture à 30% Rp 0,2

b) <u>essais sur éprouvettes entaillées - précriquées</u>
Le principe des essais est d'utiliser des éprouvettes comportant un site d'initiation (préfissure) et d'en étudier le développement (propagation) en présence d'une contrainte et d'un milieu corrosif. On espère s'affranchir ainsi du processus aléatoire d'initiation et de plus, avoir la possibilité d'étudier la propagation sur des matériaux insensibles à l'initiation (par exemple le titane en milieu marin).

L'analyse quantitative du phénomène de fissuration s'effectue en utilisant les concepts de la mécanique de la rupture, ce qui permet d'associer aux dimensions de fissure, de pièces et aux contraintes appliquées un facteur K exprimant l'intensité de contrainte en fond de fissure.

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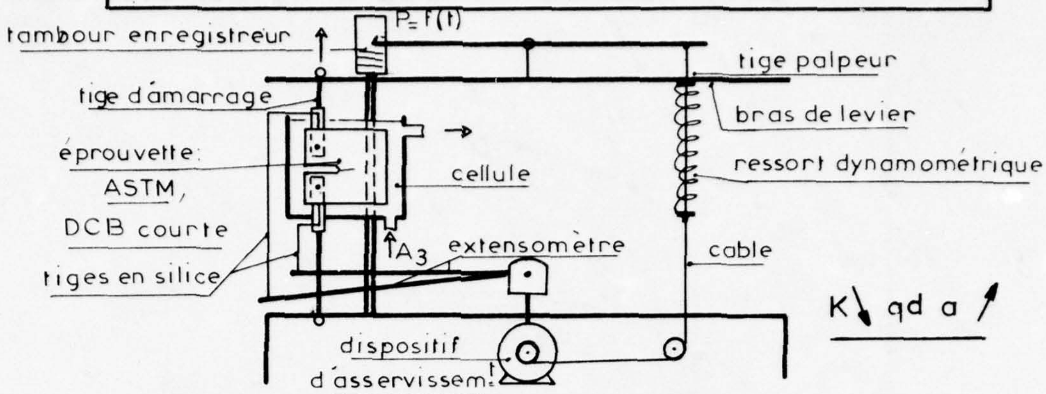
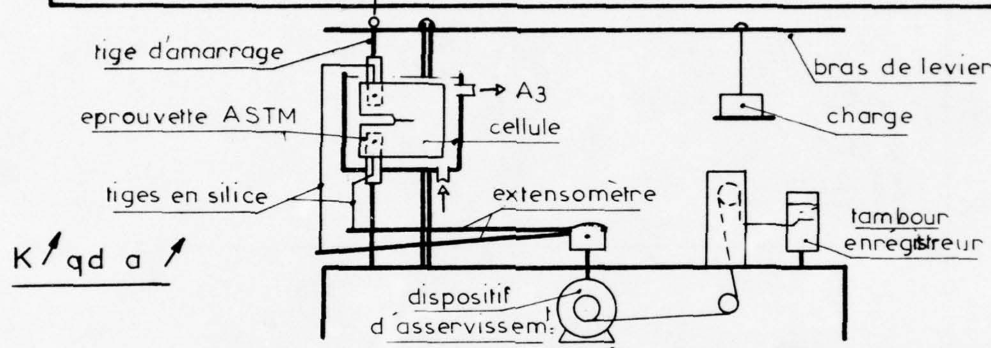
Deux types d'essais peuvent être envisagés :

DISPOSITIF D'ESSAI A DEFLEXION CONSTANTE



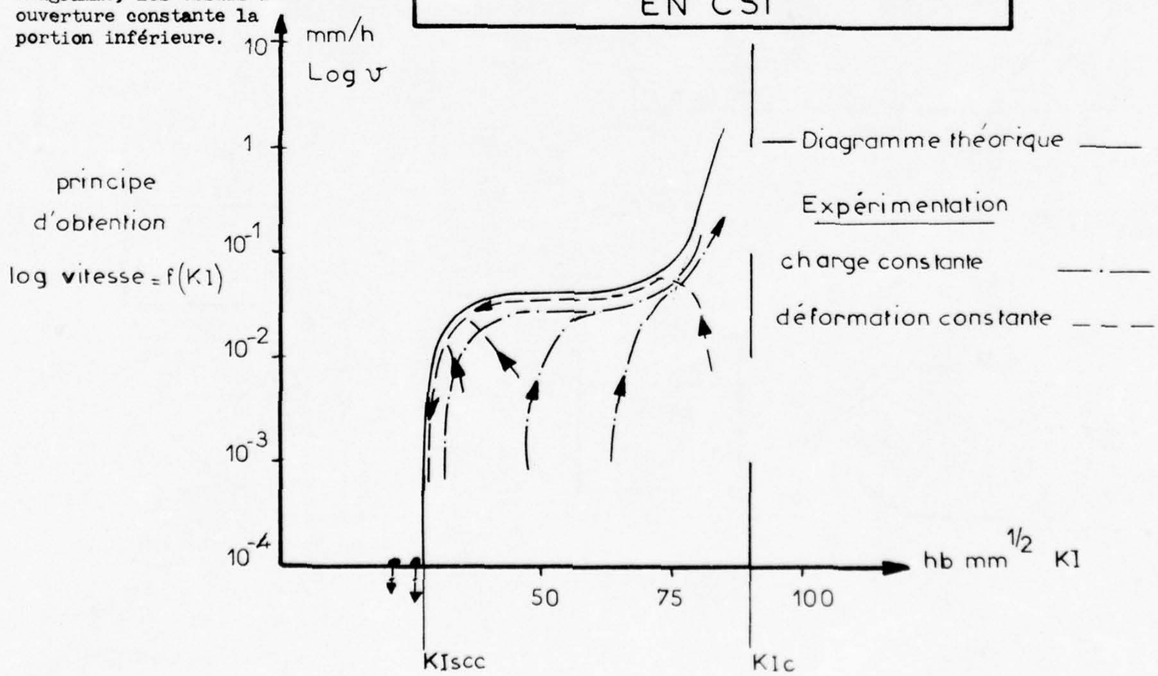
DISPOSITIF D'ESSAI A CHARGE IMPOSEE CONSTANTE



Dans les deux cas il est possible d'établir les diagrammes $\frac{da}{dt} = f(K_1)$ exprimant la cinétique de fissuration d'un matériau en CST (longueur de crique a en fonction du temps d'essai t);quand $\frac{da}{dt} \to 0$, K_1 tend vers une limite appelée K_{1scc} au-dessous de laquelle *ne se produit plus de propagation en* CST

Les essais pratiqués à charge imposée constante permettent d'atteindre la portion supérieure du diagramme, les essais à ouverture constante la portion inférieure.

PROPAGATION DES FISSURES EN CST



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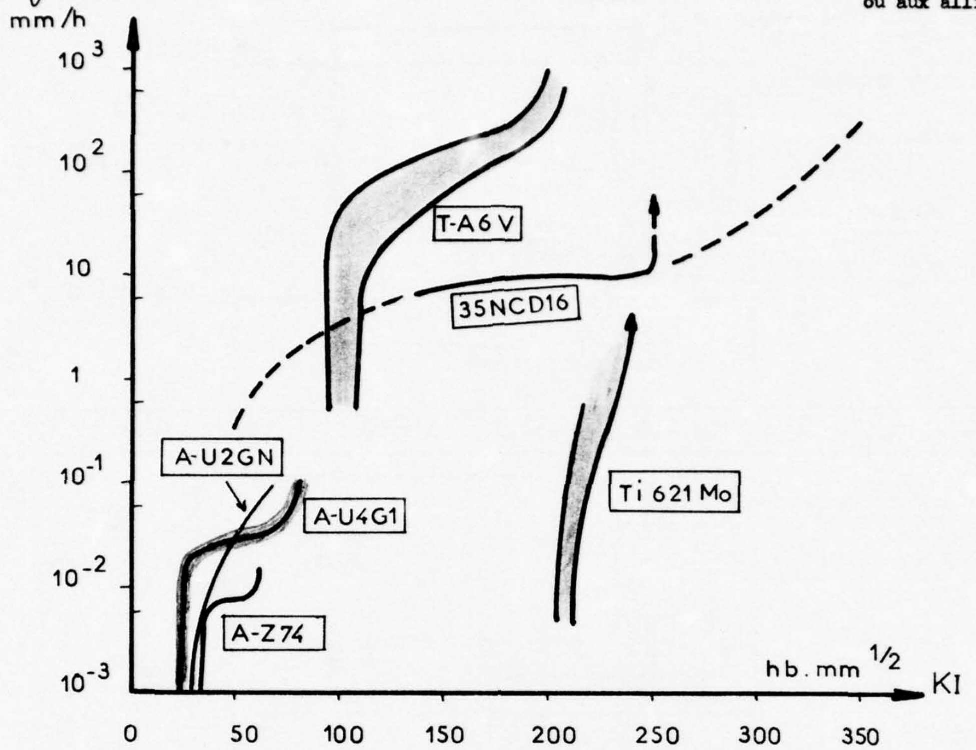
RESULTATS EXPERIMENTAUX

Ces méthodes s'appliquent aussi bien aux alliages d'aluminium qu'aux aciers ou aux alliages de titane



Essais de CST en solution NaCl 3,5 %

Influence du confinement

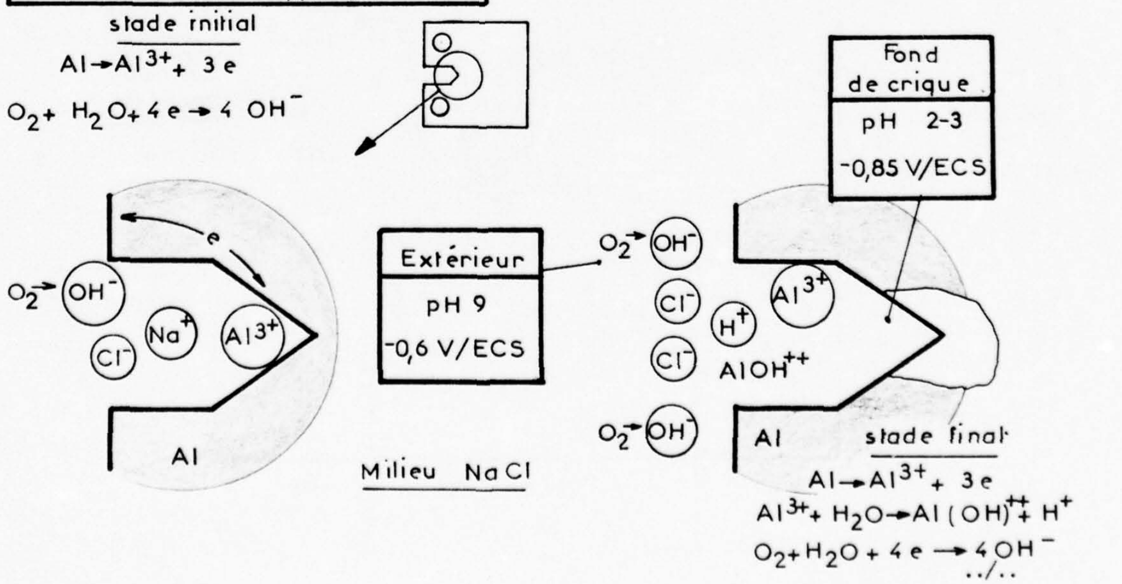
a) au sein du matériau

La propagation dans une crique est souvent une propagation en milieu confiné. Comme le montre le schéma, le pH devient très acide en fond de fissure.

CORROSION

EN MILIEU CONFINE

AW-Béthune



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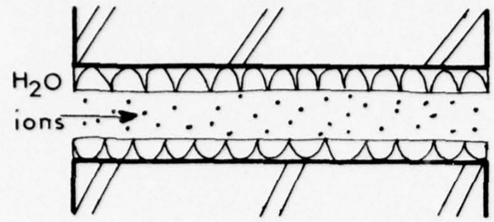
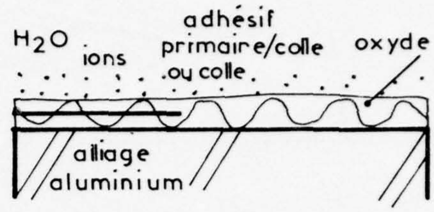
b) en surface

Nous avons déjà cité la corrosion filiforme en exemple de propagation superficielle en milieu confiné.
Un autre cas fréquent de propagation en milieu confiné est la dégradation des structures alliages légers collées qui se traduit par :

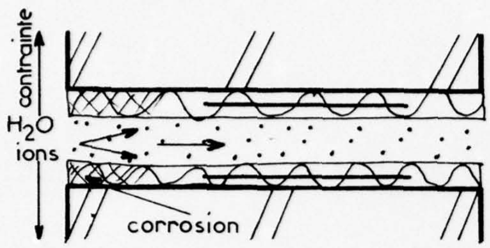
1) - une pénétration du milieu ambiant dans l'adhésif
2) - une destruction de la couche d'oxyde superficielle
3) - une corrosion et propagation de fissure.



phase 1 Pénétration



phase 2 Destruction de l'oxyde

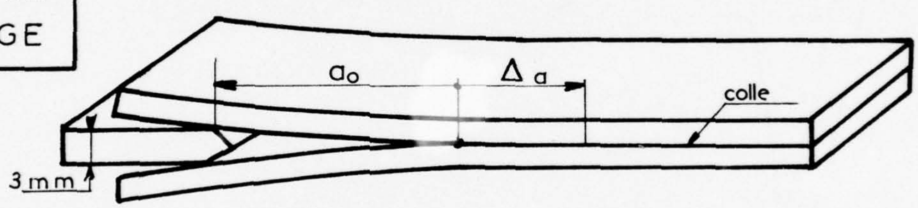


phase 3 Corrosion propagation

CORROSION DES ASSEMBLAGES COLLES

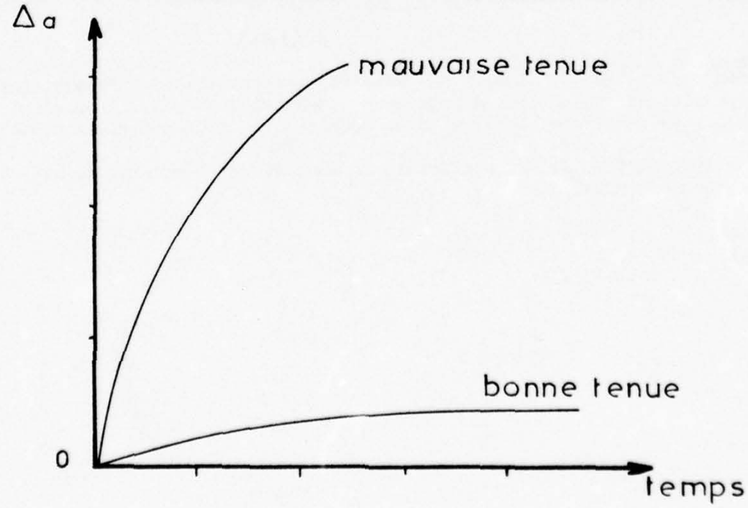
L'étude de la propagation des décollements en ambiance humide a été mise au point par BOEING (3).
Deux tôles minces collées sont soumises, à l'aide d'un coin, à une déformation constante.

ESSAI DE CLIVAGE



On mesure la propagation de crique Δ a en ambiance humide ou autre milieu

TENUE EN VIEILLISSEMENTS DES COLLAGES PAR ESSAI DE CLIVAGE

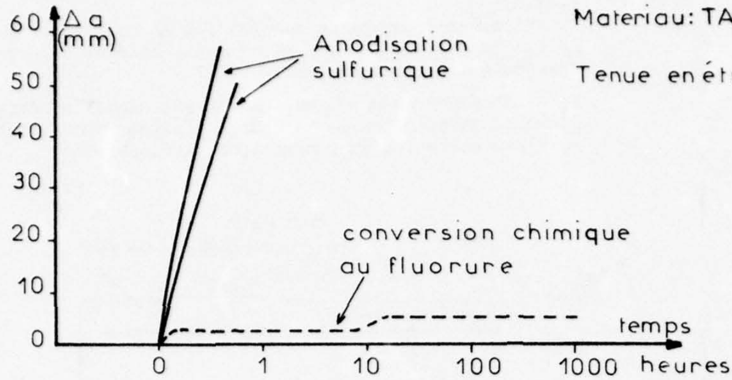


ESSAI DE CLIVAGE

Nous avons utilement appliqué cette méthode aux alliages de titane.

Materiau: TA6V collé par BSL 312.4

Tenue en étuve humide 40°C 80% HR



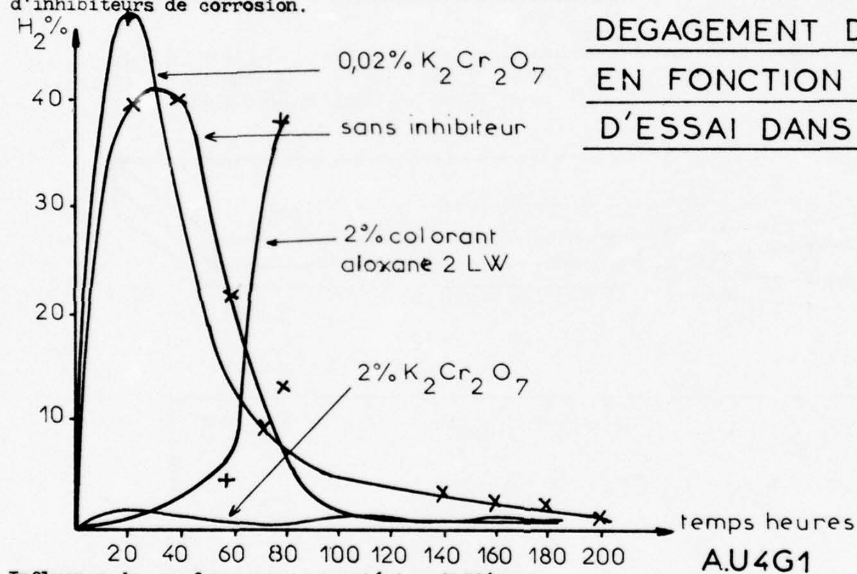
c) dans un assemblage

Un autre type de corrosion en milieu confiné a été observé dans les structures sandwichs en Nida A-G3 (5052). Un suivi original de la corrosion en laboratoire a été de mesurer la quantité d'hydrogène dégagé au cours de la réaction.

Le dosage peut être effectué par chromatographie.

Cette méthode a permis d'étudier l'influence d'inhibiteurs de corrosion.

DEGAGEMENT D'HYDROGENE EN FONCTION DU TEMPS D'ESSAI DANS H_2O DISTILLEE



Influence du couplage avec un matériau différent

Les couples galvaniques sont, dans les assemblages mal étudiés, responsables de dégradations importantes. Il est d'usage de classer les matériaux en fonction de leur potentiel d'abandon en solution corrosive (potentiel de dissolution) et de considérer la gravité du couple entre deux matériaux comme fonction de la différence de potentiel.

Cette évaluation n'est pas suffisante. Il est préférable de considérer le courant de corrosion qui, dans ce cas précis est directement mesurable.

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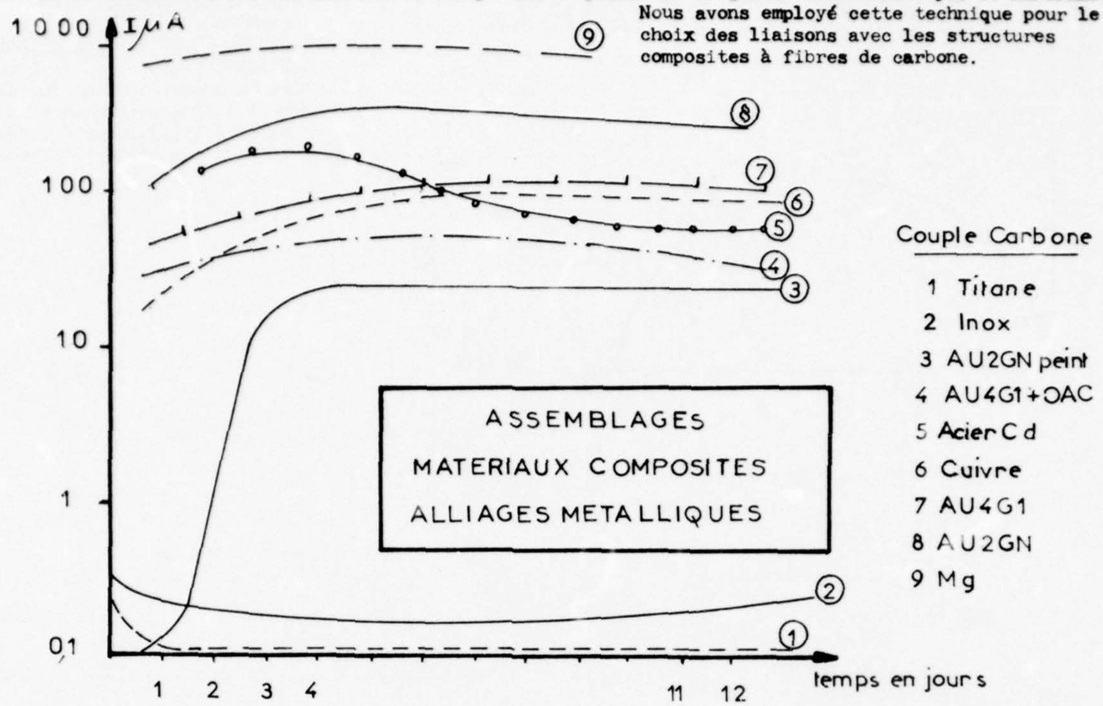
Il est possible de mesurer le courant sans perturber le circuit à l'aide d'un ampèremètre à résistance nulle. La corrélation entre ces mesures et les pertes de poids a largement été étudiée par F. MANSFELD(4)

Nous avons employé cette technique pour le choix des liaisons avec les structures composites à fibres de carbone.



Influence de la structure métallurgique

Sur un alliage -, la corrosion en milieu humide est toujours due à l'existence de zones anodiques et de zones cathodiques comme dans le cas d'un couplage de matériaux. Ces zones sont alors microscopiques : joints de grains, composés définis, matrice... C'est le cas de la corrosion intercristalline rencontrée fréquemment sur les profilés en A-U4G1 ('2024) à l'état T4 (corrosion par exfoliation).

Cette corrosion a pu être reproduite en laboratoire par un essai cyclé en brouillard salin acétique. Le cycle comprend: 45 mn de brouillard salin 35°C (5% NaCl pH 3 avec $CH_3CO\,OH$)

2 h séchage 60°C

3 h 15 mn brouillard d'eau 35°C

Sur matériaux sensibles, l'exfoliation apparaît en quelques jours.

Nous avons essayé sans succès d'appliquer cet essai à l'étude des matériaux protégés par peintures.

Pour ce cas particulier, l'exfoliation peut être reproduite par un essai d'immersions-émersions alternées:

- immersion 2 h solution NaCl 3% pH 8
- émersion 2 h humidité relative 80 - 98%
  température 35°C

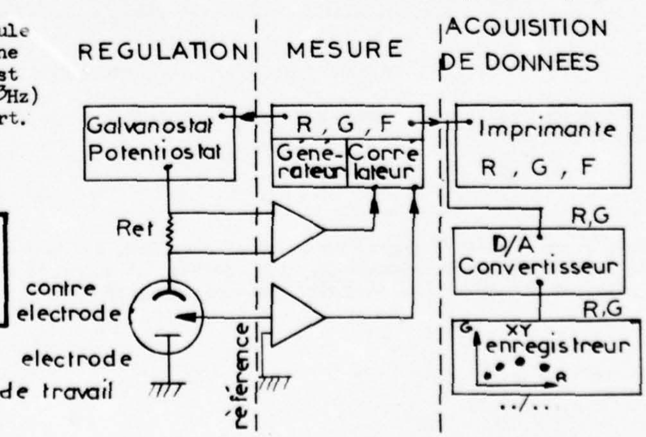
Les gammes de peinture appliquées sur alliage sensible sont ainsi sélectionnées par cet essai limité à une durée de 1500 h. Aucune corrosion ne doit être détectée sur l'éprouvette préalablement rayée en croix jusqu'au métal. (quelques piqûres ne dépassant pas 1 mm à partir des rayures sont tolérées).

Ces corrosions étant dues à l'existence de micropiles, il n'est pas possible de faire une mesure directe du courant de corrosion. Nous avons vu qu'il fallait faire appel à l'étude des courbes tension-courant ou aux diagrammes d'impédance (EPELBOIN (5)).

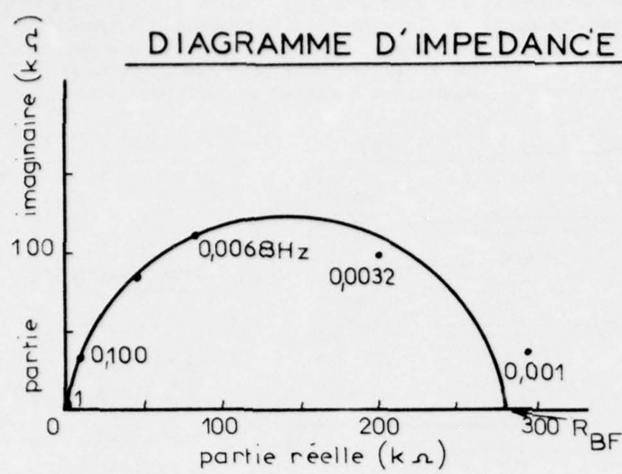
L'application des mesures d'impédance faradiques aux mesures de corrosion n'est pas encore très développée. nous avons utilisé avec succès cette méthode pour le contrôle de l'anodisation des alliages légers.

En général, la qualité d'une anodisation est contrôlée par un essai de brouillard salin. Cet essai étant long et difficilement chiffrable, nous avons tenté d'utiliser la méthode de mesure des impédances pour remplacer ce contrôle (6)

L'éprouvette anodisée est placée dans une cellule électrochimique à trois électrodes contenant une solution de chlorure de sodium. L'impédance est mesurée en fonction de la fréquence (10^4 à 10^{-3}Hz) à l'aide d'un analyseur de fonction de transfert.

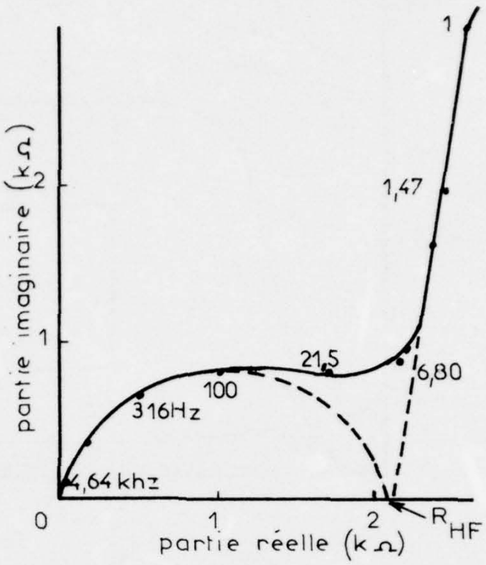


PRINCIPE DE LA MESURE D'IMPEDANCE FARADIQUE

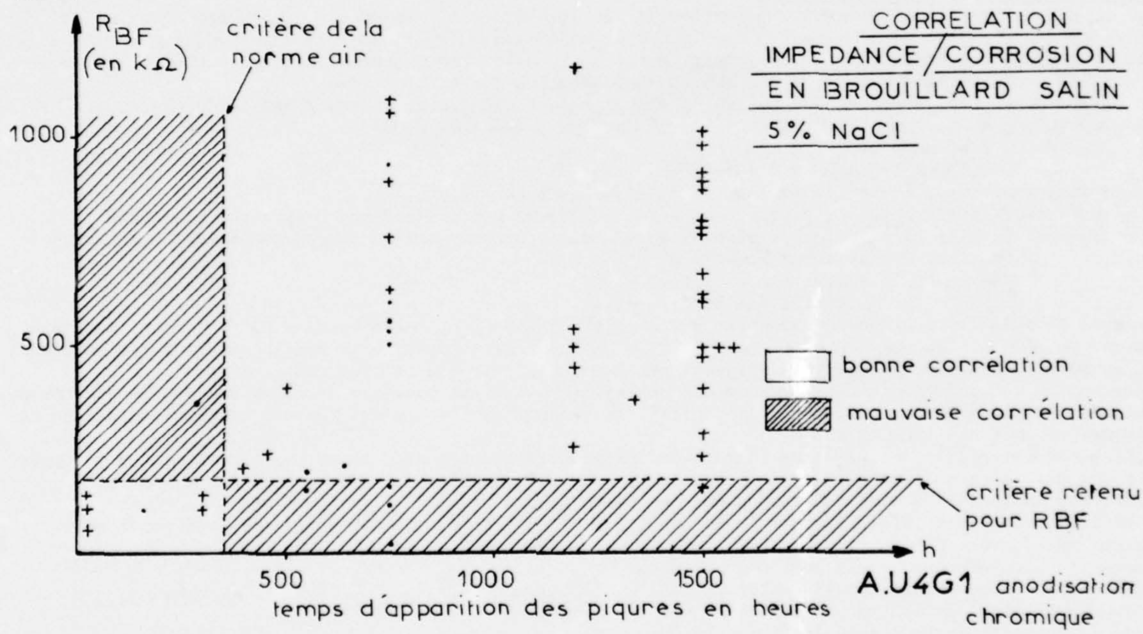


A.U4G1 anodisé
milieu NaCl

L'impédance représentée dans le plan complexe montre deux arcs capacitifs.
Il semble qu'aux fréquences élevées l'arc soit lié à la nature de la couche protectrice alors qu'aux basses fréquences l'impédance soit fonction des discontinuités du film protecteur (6).



Nous avons trouvé une étroite corrélation entre le diamètre de l'arc basse fréquence RBF et la tenue en brouillard salin.



Cette mesure maintenant entièrement automatisée peut être facilement introduite comme moyen de contrôle industriel.

Nous avons montré, à partir de quelques exemples, les possibilités des essais de laboratoire. Ces essais doivent utilement être employés simultanément et comparés à des essais prolongés en ambiance naturelle (stations de corrosions marines, industrielles, tropicales...)

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5 - DETECTION DE LA CORROSION

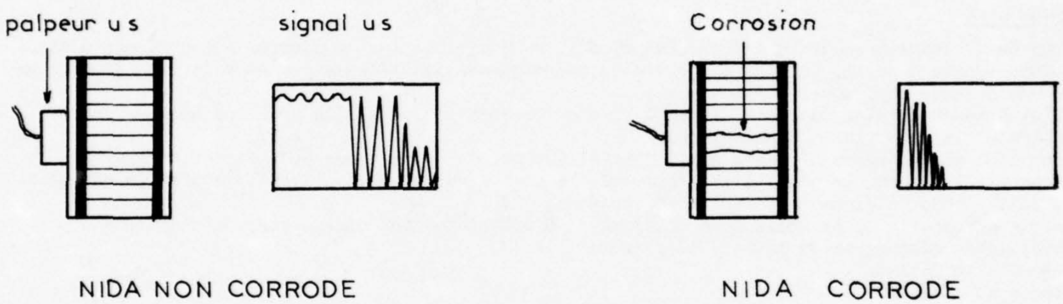
La détection de la corrosion doit aussi être une préoccupation primordiale. En effet, une corrosion découverte avant le stade de propagation sera facilement réparable. Par contre, si la propagation est importante, la réparation s'avèrera difficile, voire impossible.

A - Initiation

La nature nous a, ici, facilité la tâche puisque la corrosion se produit toujours avec formation d'oxydes abondants et révélateurs.
Les initiations de corrosion sont donc recherchées visuellement en s'aidant éventuellement de loupes, microscopes, endoscopes...
Sont ainsi découvertes toutes les corrosions superficielles, piqûres, corrosion filiforme... sur les surfaces libres.
Dans les assemblages et les endroits difficilement accessibles, la corrosion pourra être recherchée par des méthodes de contrôle non destructif telles que la radiographie, les ultra-sons ou les courants de Foucault.
Par exemple, dans une structure sandwich, la détection de la corrosion du Nid d'abeilles en alliage léger peut s'effectuer par la méthode du pulse écho.
Des étalonnages soignés permettent d'obtenir le maximum de contraste entre partie saine et partie corrodée.

CORROSION NIDA

Detection par ultra sons

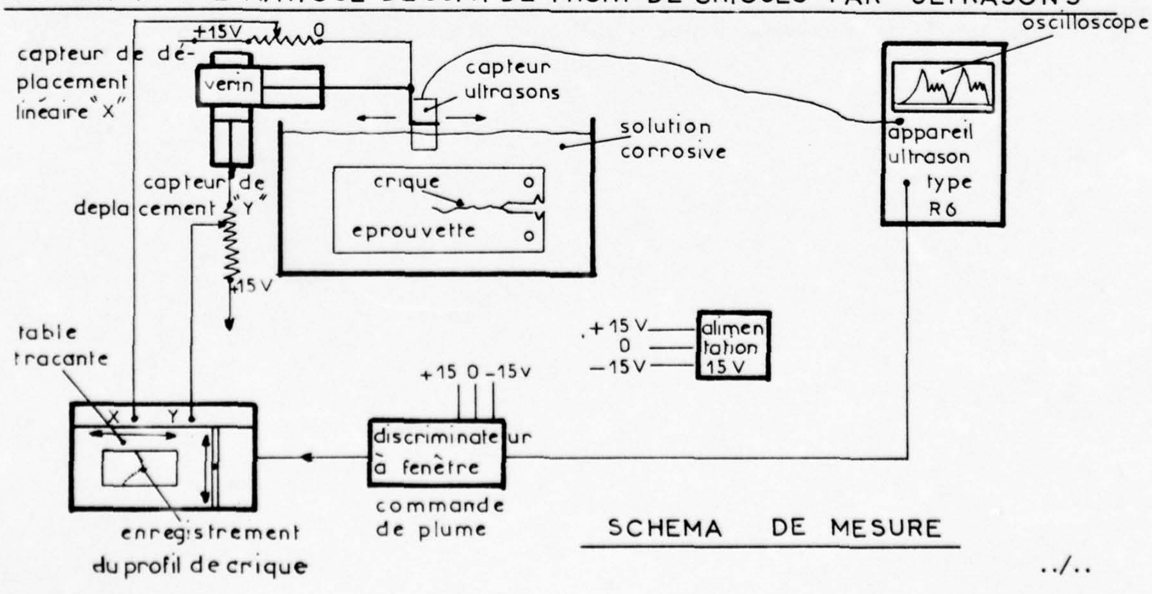


La présence d'eau peut également être détectée par ultra-sons ou mieux, à l'aide des rayons X.

B - Propagation au sein du matériau

Une propagation intercristalline ou transcristalline est plus difficilement détectable. Les moyens de recherche sont ceux employés pour les détections de criques : radiographie X, ultra-sons, courants de Foucault...
En laboratoire, a été mis au point, par exemple, un suivi automatique de crique par ultra-sons sur éprouvettes de CST.

DISPOSITIF PNEUMATIQUE DE SUIVI DE FRONT DE CRIQUES PAR ULTRASONS



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C - Propagation superficielle

C'est le cas, par exemple, de la propagation dans les assemblages collés. Les techniques de détection des décollements sont ici employées avec succès :

- contrôle au son (en tapotant légèrement la surface à contrôler)
- contrôle à la ventouse (limitée aux tôles minces)
- contrôle par ultra-sons
- contrôle par résonance sonique (Fokker bond tester, Sonic resonator, coindoscope, sondicator...)
- contrôle par méthodes Eddy sonic (courants de Foucault)
- contrôle par interférométrie holographique
- contrôle par les méthodes thermographiques
- contrôle par rayons X.

Parmi toutes ces méthodes, aucune ne peut être considérée comme universelle; le choix de la méthode dépend de nombreux paramètres :

- dimensions minimales du défaut recherché
- géométrie de la pièce
- localisation du défaut (accessibilité)
- matériau
- disponibilité d'appareillage
- coût
- facilité de mise en oeuvre.

Il est parfois utile d'utiliser deux méthodes de contrôle différentes, de façon à bien détecter et identifier les corrosions présumées.
En service, certaines zones reconnues, d'après l'expérience, susceptibles à la corrosion, seront contrôlées périodiquement.
Dans le cas d'un incident sérieux sur un avion, un contrôle statistique sera effectué sur d'autres appareils du même type afin de définir si un contrôle systématique s'avère nécessaire.
Ainsi, les examens fréquents et le bon sens permettront le plus souvent la détection rapide et éviteront que la corrosion nécessite des réparations trop coûteuses ou provoque des accidents graves.

6 - CONCLUSION

Ce bref aperçu de quelques méthodes d'essais montre, s'il en était besoin, la diversité des moyens d'étude de la corrosion. Petit à petit, la mise en oeuvre de techniques scientifiques permet à la corrosion de ne pas demeurer une science empirique.
Toutefois, l'expérience acquise dans les divers laboratoires sera toujours d'un précieux secours pour l'interprétation et la prévision des phénomènes.
La comparaison d'un grand nombre d'essais et la statistique seront nécessaires pour éviter de graves méprises, en particulier pour la phase d'initiation de la corrosion que nous n'avons pas traitée en détail ici mais qui fait l'objet d'études nombreuses et variées (7).
Dans l'industrie aéronautique, le choix d'un matériau et d'une protection est un compromis entre :

- propriétés mécaniques et masse - ($\frac{R}{d}$, ténacité ...)
- tenue à la fatigue
- tenue au fluage
- tenue à la corrosion (CST, fatigue corrosion...)
- prix de revient

Par exemple, une insensibilité totale à la CST peut être obtenue, sur alliage léger à durcissement structural, par sur-revenu. Cet état conduit généralement à :

- une chute des caractéristiques mécaniques
- une diminution de la limite de fatigue
- une vitesse de propagation de criques en fatigue plus importante.

Ainsi, dans certains cas, un certain niveau de susceptibilité à la CST devra être toléré pour maintenir les autres propriétés. Mais, pour ce faire, il est nécessaire de connaître parfaitement les risques encourus et d'avoir un moyen de détection efficace. Notre exposé a montré dans quelques cas particuliers les moyens mis à notre disposition.
Cette liste est loin d'être limitative, car chaque nouveau problème de corrosion nécessite presque toujours la mise au point d'un essai et d'une détection particulière.
Retenons, pour terminer, qu'il vaut mieux prévenir que guérir et que tous les essais conduisent à diminuer très sensiblement le coût de la maintenance tout en améliorant la fiabilité.

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CORROSION: STUDY AND DETECTION

by

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SUMMARY

Two lines of approach to the study of corrosion phenomena are examined in parallel: corrosion reproduction and acceleration tests; and determination of corrosion rates.

Accelerated Corrosion Tests

Various types of test have been developed for the reproduction and acceleration of natural phenomena. In the aeronautical field, for example, salt spray, continuous and alternating immersion, and climatic cycle tests are used, together with exposure to marine and tropical environmental conditions. These types of test are adapted in each case to the actual problem involved. We shall demonstrate the development and utilization of these tests by a series of examples.

Measurement of Corrosion Rates

The rate of corrosion is obviously a valuable tool for forecasting damage resulting from this phenomenon, and its measurement is therefore amply justified. We describe the methods used in this context by the Aérospatiale Central Laboratory, in particular the use of potentiostatic curves and measurement of impedance at low frequencies. The application of these methods to the testing of anodizing demonstrates the advantage of this type of method. In the context of stress corrosion cracking, the study of the kinetics of crack propagation likewise represents a powerful method of investigation and forecasting.

Detection Methods

Whilst visual inspection frequently reveals traces of corrosion, the use of non-destructive test methods such as radiographic, ultrasonic, holographic, eddy current, etc., are extremely valuable. On the basis of actual cases encountered in the aeronautical field (intergranular corrosion and stress corrosion cracking of aluminium alloys, confined atmosphere corrosion of honeycomb structures, filiform corrosion under paint, etc.) the present paper demonstrates the possibilities and limitations of corrosion study and detection methods.

1. INTRODUCTION

In a large number of industrial fields, there now exists a full awareness of the heavy costs incurred due to corrosion and the repair of damage attributable to this phenomenon. For example, the total cost of corrosion in Germany for 1968 was estimated at $9,000 million.

It was estimated that at least $3,000 million could have been saved, if more suitable solutions had been adopted. Thus research laboratories have been led to concentrate more and more on understanding and forecasting this phenomenon, which has proved so costly, with the added risk in the aeronautical industry of serious consequences with respect to passenger safety.

The Aerospatiale Central Laboratory has been working on these problems for over 20 years, and has acquired very considerable experience in the field of corrosion testing and detection. Some indications of this experience are given in the present paper, with particular reference to light alloys which are basic materials used in the aeronautical industry.

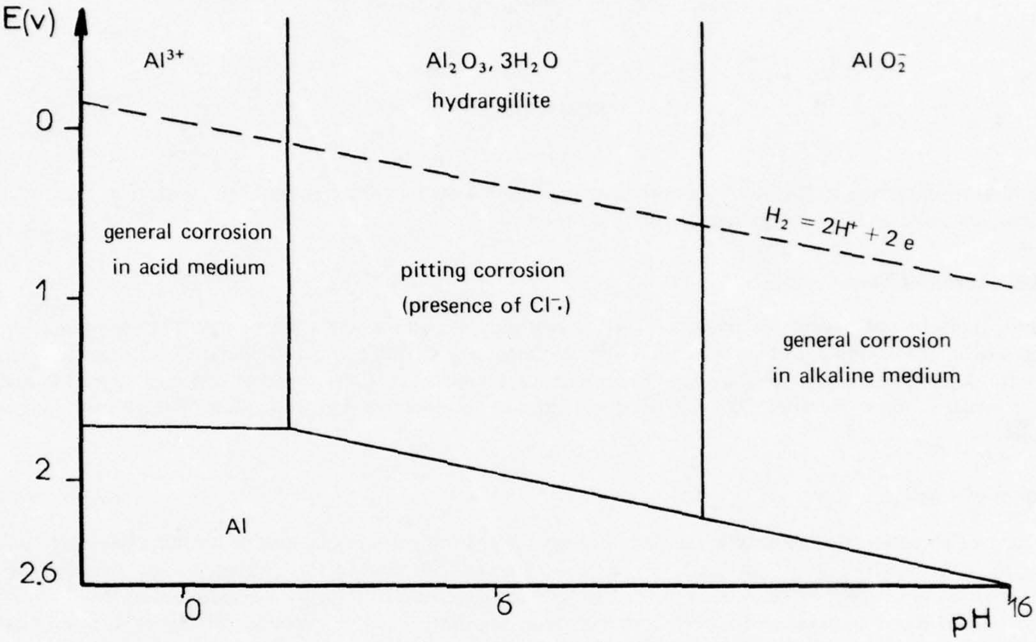
2. THERMODYNAMIC AND KINETIC ASPECTS

Thermodynamic

It is theoretically possible to forecast whether or not a chemical reaction can occur in the case of corrosion in an aqueous medium, and knowledge of the thermodynamic tension/pH diagram (Pourbaix Diagram) enables us to determine the possibilities of corrosion.

For example, the diagram for aluminium demarcates the areas of general corrosion and pitting corrosion.

Pourbaix Diagram



Tension/pH balance diagram for aluminium (water at 25°C)

Towards the highly acid pH values, there is an area of general corrosion with formation Al^{3+} ions. We can mention corrosion in a confined atmosphere, for example under paint (filiform corrosion) or in the case of bonded assemblies.

Over a vast range (pH 2 to 10), aluminium is covered with a passive layer of alumina. Faults in this protective layer lead to pitting corrosion. This type of local attack is frequently encountered with light alloys.

For alkaline pH values, we find general corrosion with formation of $Al\ O_2$ aluminate ions. This type of deterioration is infrequent on aircraft, but can occur in the vicinity of the accumulators.

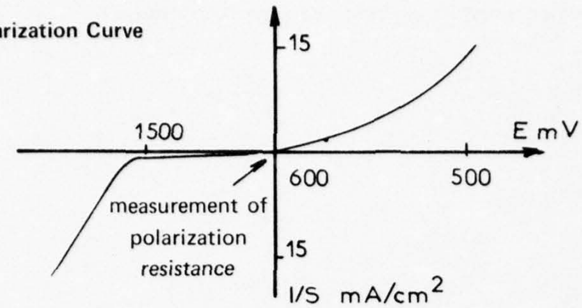
Kinetics

The kinetics of deterioration of these different pH values can be determined by electro-chemical measurement (in the case of the activation reaction).

- Tracing of potential amplitude curves, determination of corrosion current by extrapolation of Tafel straight lines (Evans diagram); measurement of polarization resistance, inversely proportional to corrosion current in the majority of cases.
- Trace of corrosion potential for reactive impedance diagrams, giving polarization resistance Rp for simple cases, low frequency resistance Rt being inversely proportional to corrosion current, and double-layer capacitance.

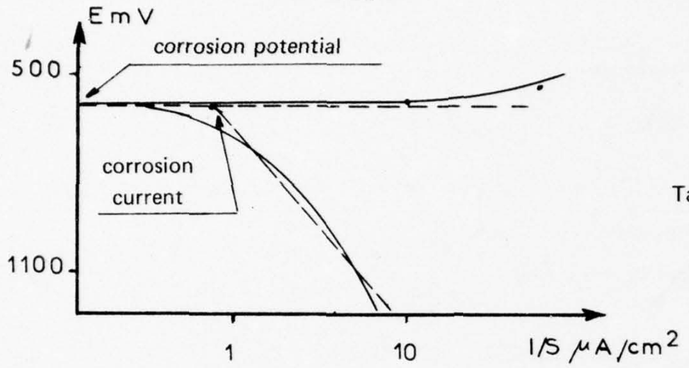
Simple measurements of weight loss frequently give a useful indication.

Polarization Curve



A-U4G1 in NaCl 3% + $K_2Cr_2O_7$ 5.10^{-3}M

Evans Diagram

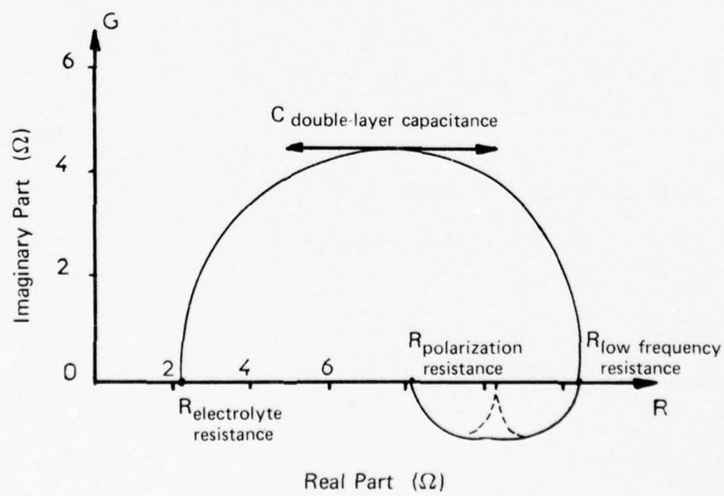


Tafel law: $E = a + b \log i$

Whilst these methods can be applied for general surface corrosion, their application is more difficult in the case of localized corrosion.

As we shall see, other methods can be used to monitor the reaction. In the case of stress corrosion cracking, propagation kinetics can be determined by monitoring the progress of the cracking phenomenon.

Reactive Impedance Diagram



Armco iron in sulphuric medium (according to I.Epelboin (CNRS))

3. PRINCIPLES OF CORROSION STUDY

Whilst it is generally possible to classify the various types of corrosion, most cases require individual study on their own merits. Two types of question may be presented to the corrosion laboratory:

(1) Selection of a new material, and its protection.
(2) Remedial action for deterioration encountered in service.

In both cases, all parameters relating to the material and its environment must be considered.

Parameters

Material

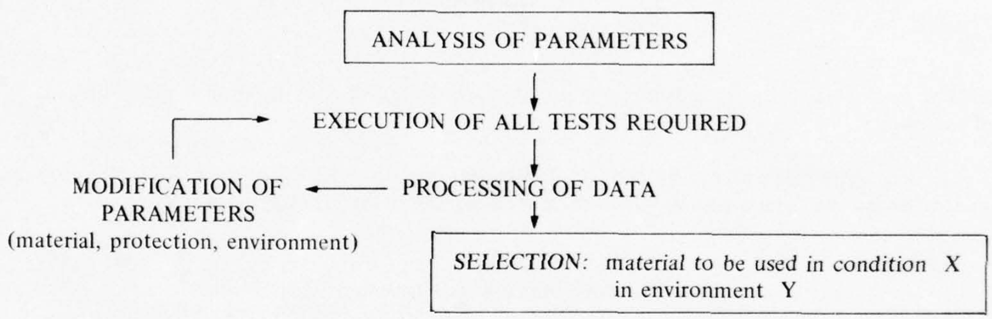
- Chemical composition
- Metallographic structure
- Surface condition
- Form of part
- Contact with other materials
- Assembly methods
- Stresses (internal and external), etc.

Environment

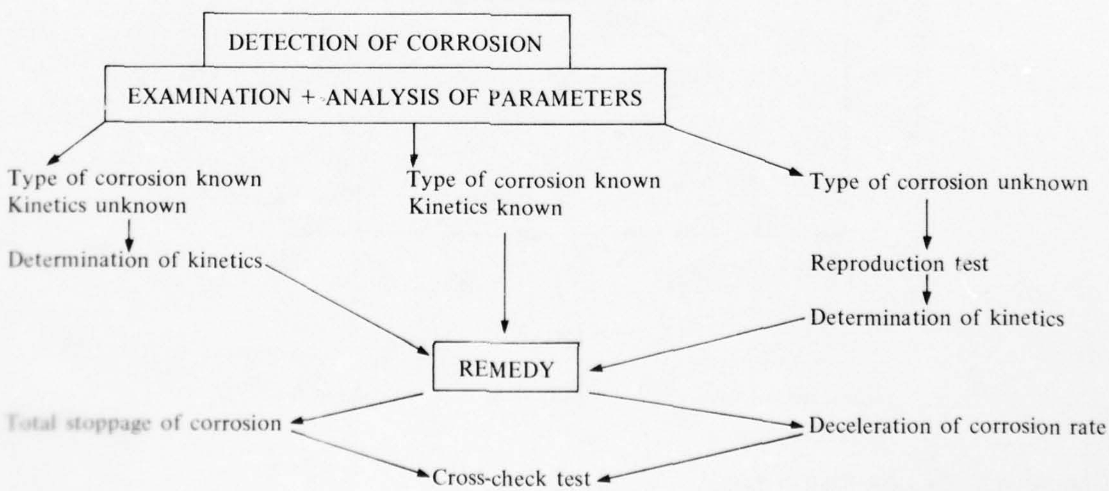
- H_2O (ambient humidity, retention, condensation)
- O_2 (ventilation)
- Ions (chlorides, sulphates, nitrates, etc.)
- pH factor
- Temperature, etc.

The study can be conducted in one of two ways:

First case: Selection of a new material and its protection.



Second case: Search for remedy for corrosion encountered in service.



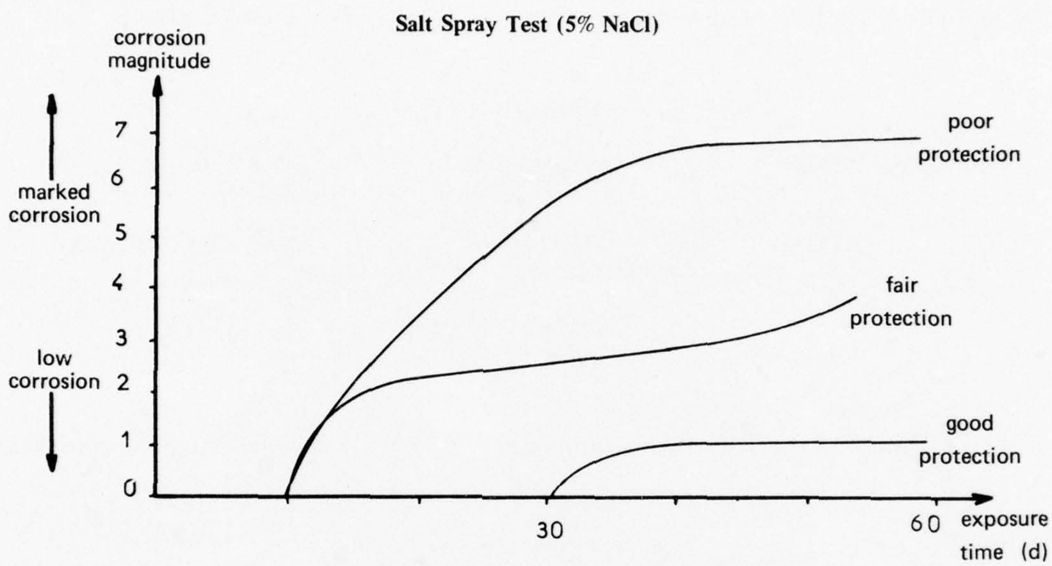
The above extremely simplified diagrams give an idea of the number of tests required for forecasting and preventing corrosion.

4. TEST METHODS

On an aircraft in service, a substantial quantity of condensate water is present in the majority of zones (tanks, sandwich structures, landing gear compartments, etc.). This water generally has a pH value of between 5 and 9, and contains chlorides in all cases.

4.1 Start of Corrosion

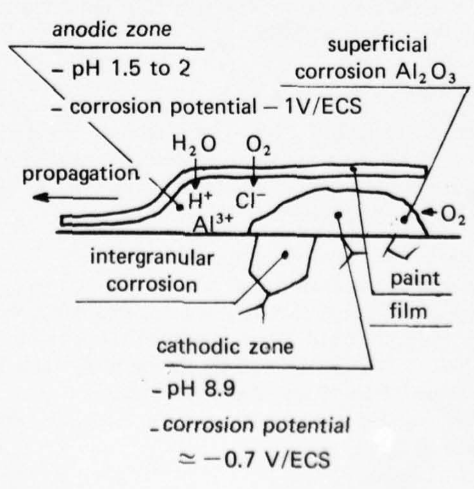
Pitting corrosion: The ambient medium is liable to initiate corrosion by breaking the layer of passive alumina. This phenomenon can be reproduced in the laboratory, using for example the salt spray test. We use a neutral pH salt spray, containing 5% Sodium Chloride at a temperature of +35°C. This test is used widely for checking protective coatings and paint. The degree of corrosion is measured against time, over a period of up to 1500 hours.



A-U4G1 protected by polyurethene paint coating

Fretting corrosion: In the case of an assembly, the start of corrosion may be caused by fretting action rather than the ambient medium. Micro-displacements under load lead to rupture of the passive layer, propagation then occurring at these points by simple corrosion, stress corrosion cracking, fatigue or fatigue-corrosion. Fretting corrosion can be reproduced in the laboratory, for example, by an assembly fatigue test, the assembly being subjected simultaneously or periodically to a corrosive environment.

Principle of filiform corrosion according to A.W.Bethune (Boeing)



Filiform corrosion: While the ambient medium may have a relatively neutral pH value, this is not the case for confined zones (under the protective layer, for example), where, as we shall see below, the pH value can become highly acid. We take the example of filiform corrosion, this being a superficial attack which can be the start of intergranular corrosion taking, for example, the form of threads running under the paint from a point of discontinuity (rivets, fuselage junction edges).

This phenomenon can be reproduced artificially in the laboratory. The test consists in subjecting a printed test piece, on which a cross has been scratched down to the metal, to hydrochloric acid vapour for a period of 30 minutes, the test piece then being placed in an oven at +40°C, with 80% relative humidity.

In the case of a defective protection under these conditions, the appearance and progress of filiform corrosion, starting at the scratches, can be observed with the passage of time. The acceptance criterion used is that the "threads" must not exceed a length of 2 mm after a test period of 40 days.

These examples demonstrate the possibilities for laboratory reproduction of corrosion initiation.

INITIATION

NEUTRAL MEDIUM	MECHANICAL (ex. fretting)	ACID MEDIUM (ex. filiform corrosion)
↓	↓	↓
PITTING	RUPTURE OF PROTECTIVE COATING	SURFACE CORROSION

PROPAGATION
(or not)

Processing of corrosion test data shows that initiation has a random nature, so that this phase of corrosion is difficult to forecast.

4.2 Propagation

Where propagation occurs in a light alloy, it can take an intergranular or transgranular form. Propagation can be influenced by a number of factors, among the principal of which we can mention: stress, confinement, coupling with a different material, and metallurgical structure.

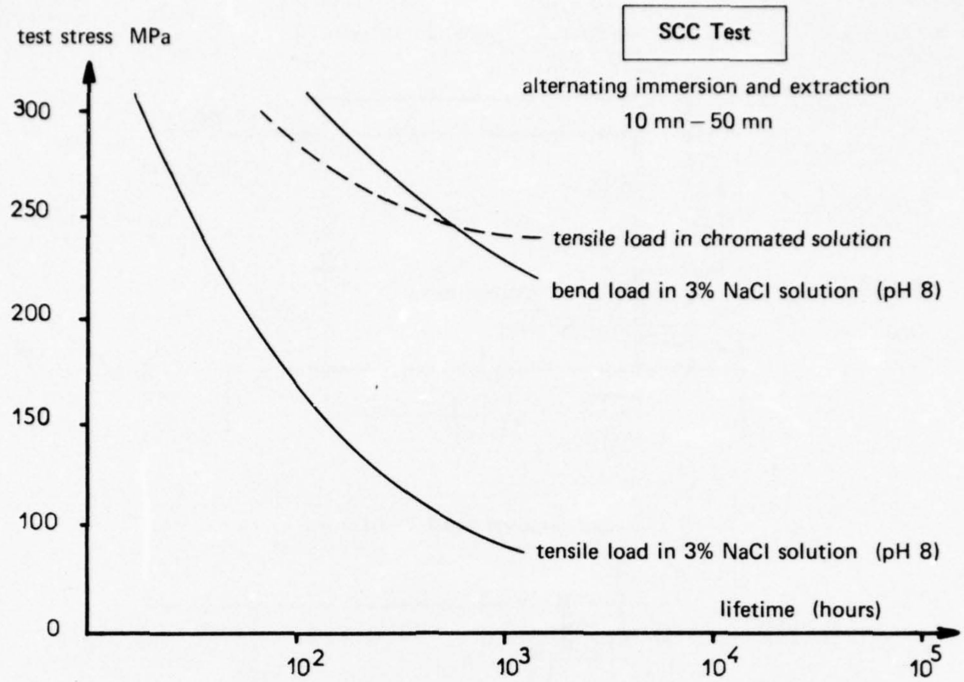
Influence of stresses: In this case, propagation takes the form of intergranular or transgranular stress corrosion cracking (SCC). Methods for SCC testing have not been standardized, and a wide variety of test rigs and corrosive media are used. Test conditions are also extremely varied. According to Brenner[1], SCC tests can be carried out using one of two types of procedure: constant imposed load or constant distortion. A major difference between these two types is that with constant imposed load, stress increases as the material weakens, while with constant distortion, stress corrosion cracking may not necessarily occur following the phenomenon of stress relief. Both methods have advantages and disadvantages, and selection depends frequently on a number of considerations: cost, form of product, service stresses, and basic studies. Thus we find more than a dozen different types of test, using bending, traction and polyaxial loads, with different forms of test piece, and involving elastic or plastic stresses.

Testing can be carried out on a smooth test piece, covering both initiation and propagation of corrosion, or on a pre-cracked sample, for the study of propagation alone.

(a) *Testing with smooth test-pieces*

Variation in lifetime is plotted against applied stress. As shown on facing page, this curve depends on the type of load and test medium. The test method must therefore be selected arbitrarily, so as to provide the simplest and most easily reproducible method possible for comparative study. Following an exhaustive study on a nation-wide scale in France, we selected the following conditions[2]:

- Samples are taken in the short transverse direction.
- Sample machining: surface roughness less than 0.7 μ CLA (VV)
  dimensions of calibrated part of test pieces: ϕ 4 mm, length 25 mm.
- Surface preparation: fluonitric stripping (AIR standard 9050 C), one minute insulation of pure NO_3H (63%) 50 cc/1 + pure FH (60%) 50 cc/1, at 95°C, followed by rinsing with water and passivation in pure NO_3H. The samples must then be tested within 24 to 48 hours after stripping.
- Application of stress (5 samples per set): recommended stress loads: 75, 50 and 30% Rp (0.2). Stress is applied by a constant load bending device.



A-Z 5 GU T 7651

- Corrosive medium (ASTM G 44-75): solution of 3.5% NaCl prepared with permutated water (ρ 1 MΩ) and pure reagent (pH 6.4 to 7.2).
- Application: immersion (10 minutes) alternating with extraction (50 minutes), 24 hours out of 24 for 30 days.
- Micrographic examination: this is designed to differentiate between mechanical rupture resulting from the formation of pitting, and rupture resulting from SCC.
- Expression of results: lifetime is expressed in days. The following classification system is also used:
  - A: no rupture at 75% Rp 0.2
  - B: rupture at 75% – no rupture at 50% Rp 0.2
  - C: rupture at 50% – no rupture at 30% Rp 0.2
  - D: rupture at 30% Rp 0.2

(b) *Testing with notched and pre-cracked test-pieces*

In this case, the principle consists in using test-pieces incorporating a corrosion initiation site (pre-crack), and to study development (propagation) of corrosion in the presence of a stress, and in a corrosive medium. In this way, it is hoped to avoid the random process of initiation, and to be able to study corrosion propagation on materials which are insensitive to initiation (for example titanium in a marine environment).

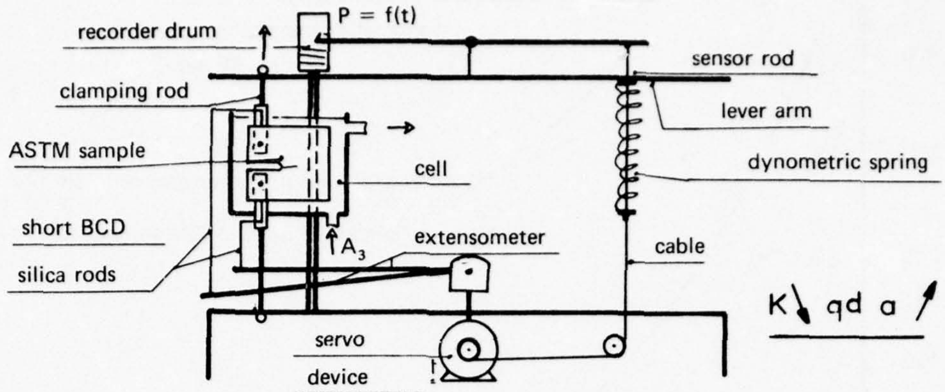
Quantitative analysis of the cracking phenomenon is achieved by using the concepts of rupture mechanics, whereby it is possible to associate a factor, K, expressing stress intensity at the bottom of the crack, with crack dimensions, part dimensions, and applied stresses.

Two types of test can be considered.

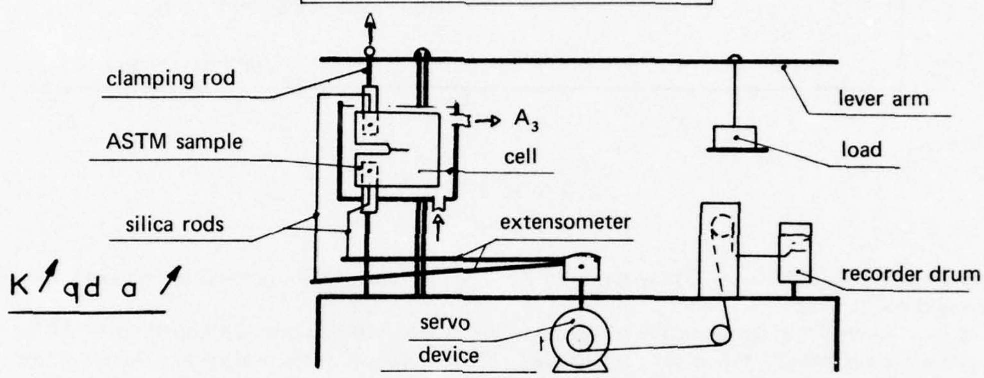
In both cases we can obtain diagrams for $\frac{da}{dt} = f(K1)$, expressing the SCC cracking kinetics of a material (crack length $\underline{a}$ plotted against test time $\underline{t}$). When $\frac{da}{dt} \to 0$, $\underline{K1}$ tends towards a limit, K1scc,, below which no further SCC propagation occurs.

Practical constant imposed load tests enable us to reach the upper portion of the diagram, and constant deflection tests the lower portion.

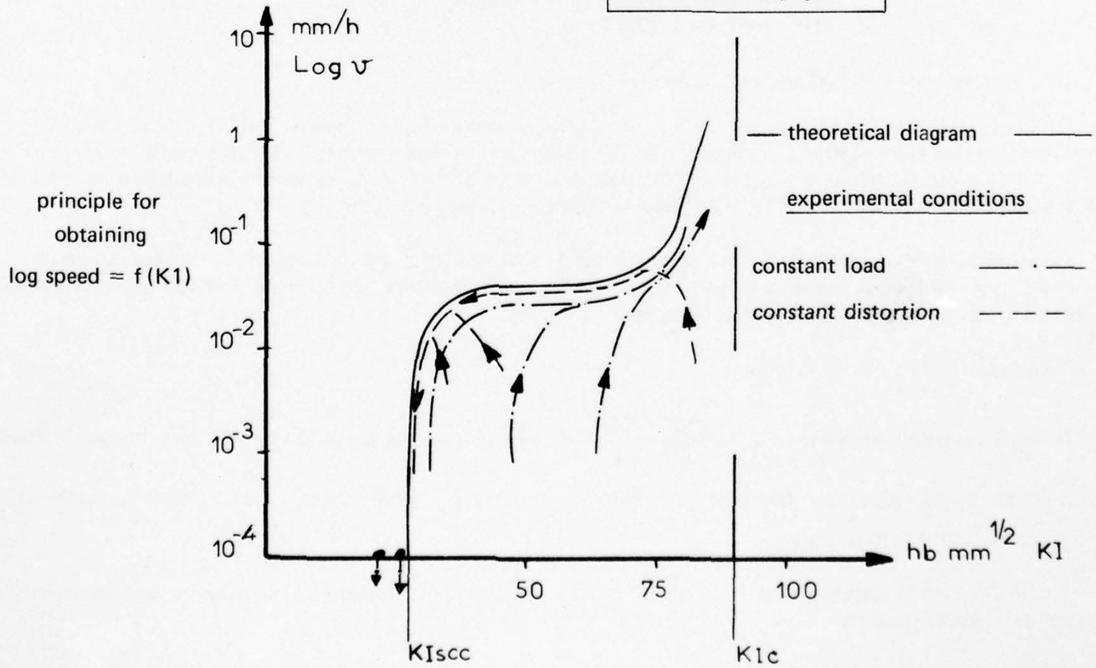
Constant Deflection Test Device



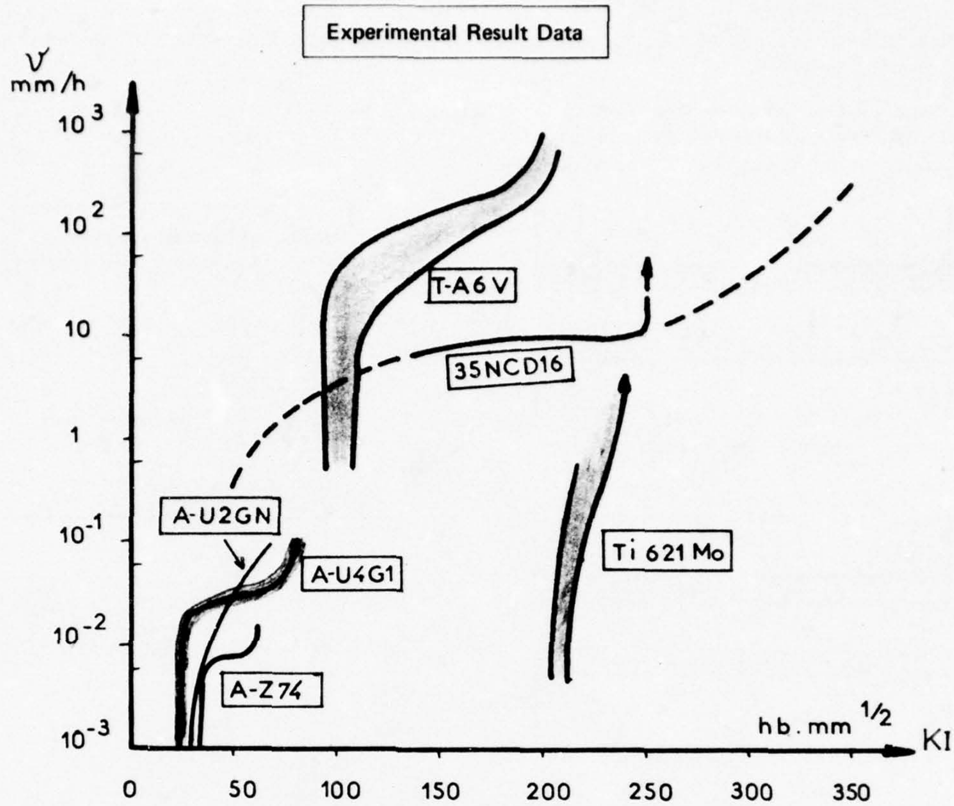
Constant Imposed Load Test Device



SCC Crack Propagation



These methods apply to aluminium alloys, steels, and titanium

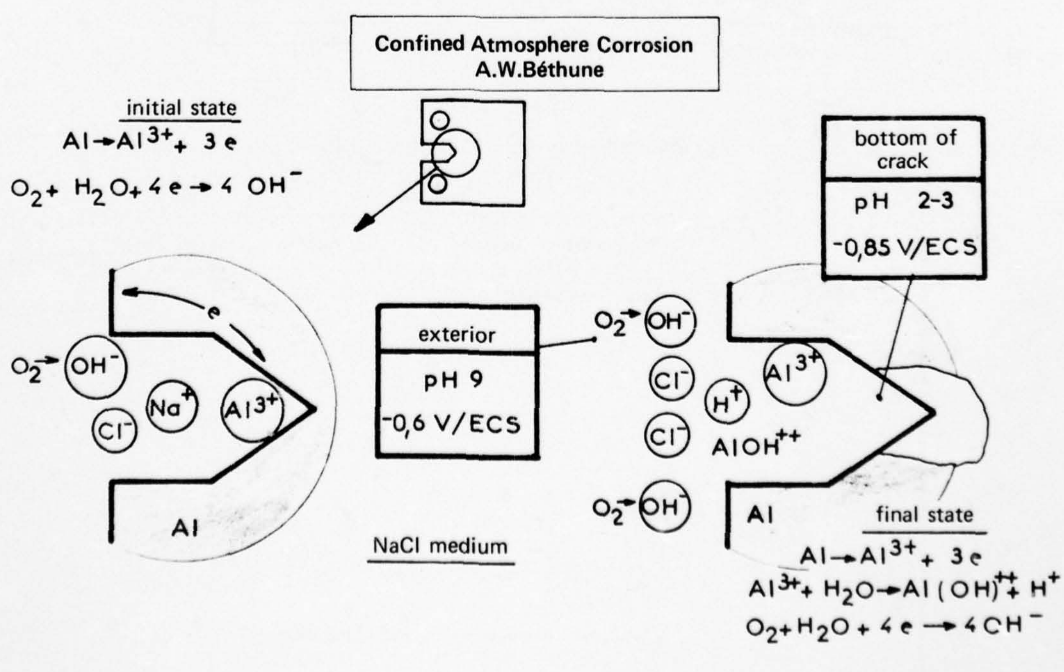


SCC tests in 3.5% NaCl solution

Influence of confinement

(a) *Within the material*

Propagation in a crack frequently corresponds to confined atmosphere propagation. As shown in the diagram, the pH value becomes extremely acid in the bottom of the crack.

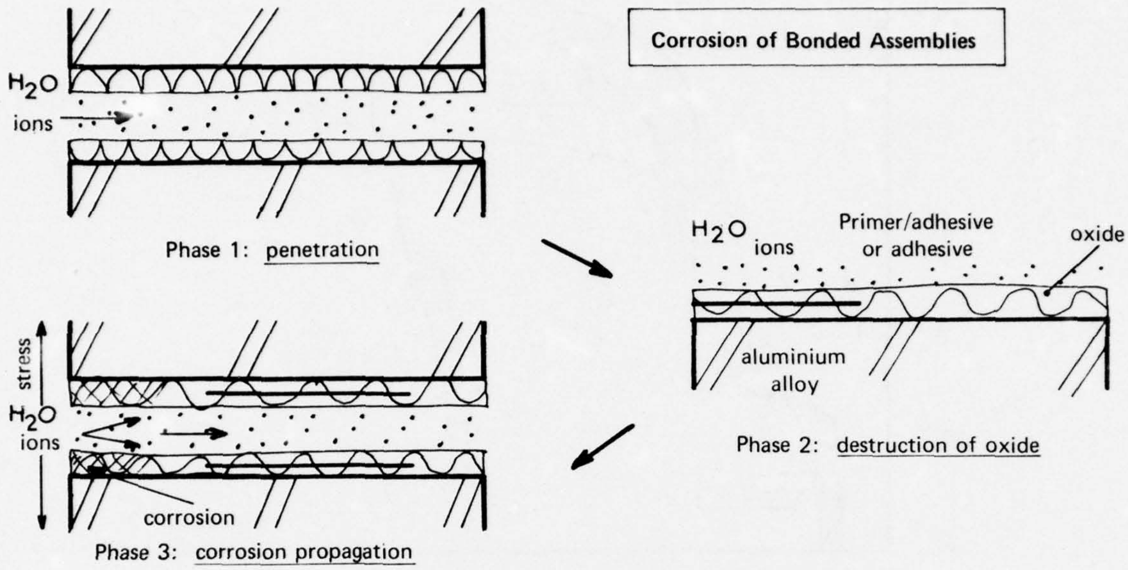


(b) *On the surface*

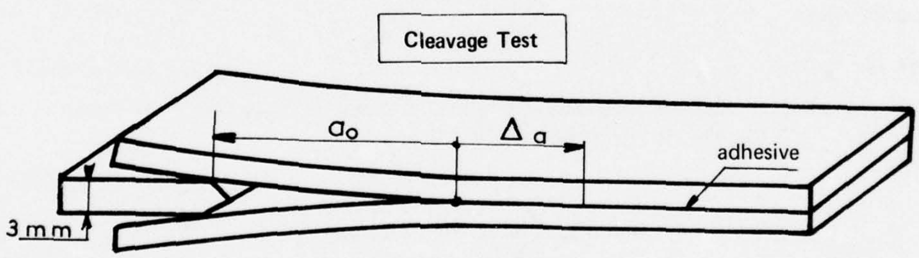
We have already quoted filiform corrosion as an example of superficial propagation in a confined atmosphere.

Another frequent example of confined atmosphere propagation is the deterioration of bonded light alloy structures; this corresponds to:

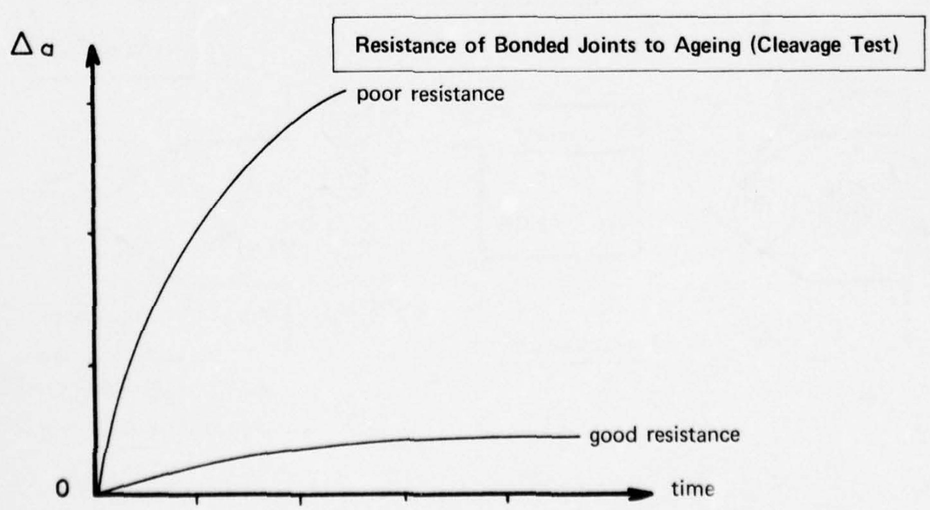
(1) Penetration of the ambient medium in the adhesive
(2) Destruction of the surface oxide layer
(3) Corrosion and propagation of cracking action.



The study of corrosion propagation in bonded joints, under humid ambient conditions, has been developed by Boeing[3]. Two bonded light gauge sheets are subjected to constant distortion, using a wedge.

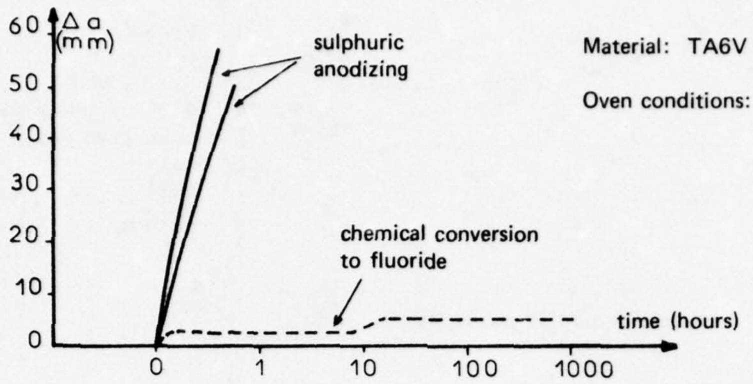


Crack propagation Δa is measured in a humid environment or other medium.



We have applied this method usefully in the case of titanium alloys.

Cleavage Test

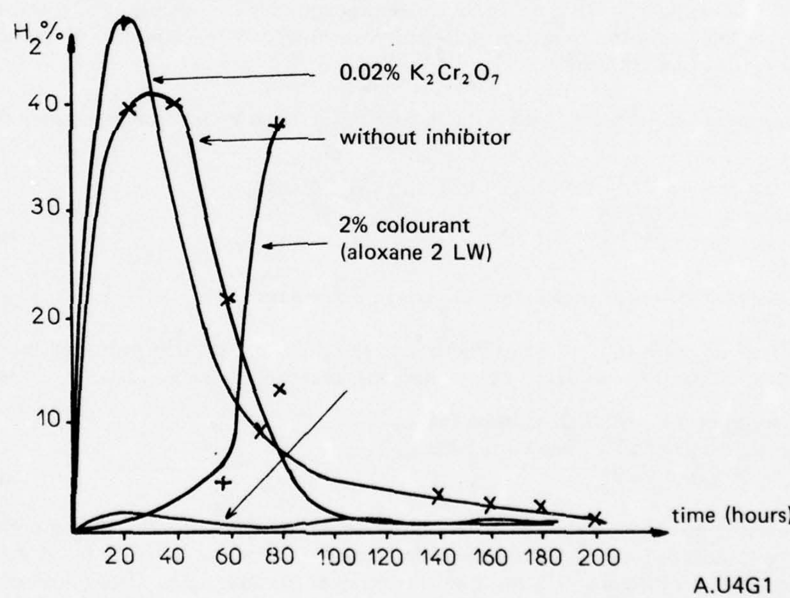


(c) *In a joint*

Another type of confined atmosphere corrosion has been observed in NIDA A-G3 (5052) sandwich structures. A novel form of corrosion monitoring in the laboratory has been the measurement of the quantity of hydrogen given off during reaction.

Dosage can be by chromatography. This method makes it possible to study the influence of corrosion inhibitors.

Release of Hydrogen According to Test Time (Distilled H_2O)

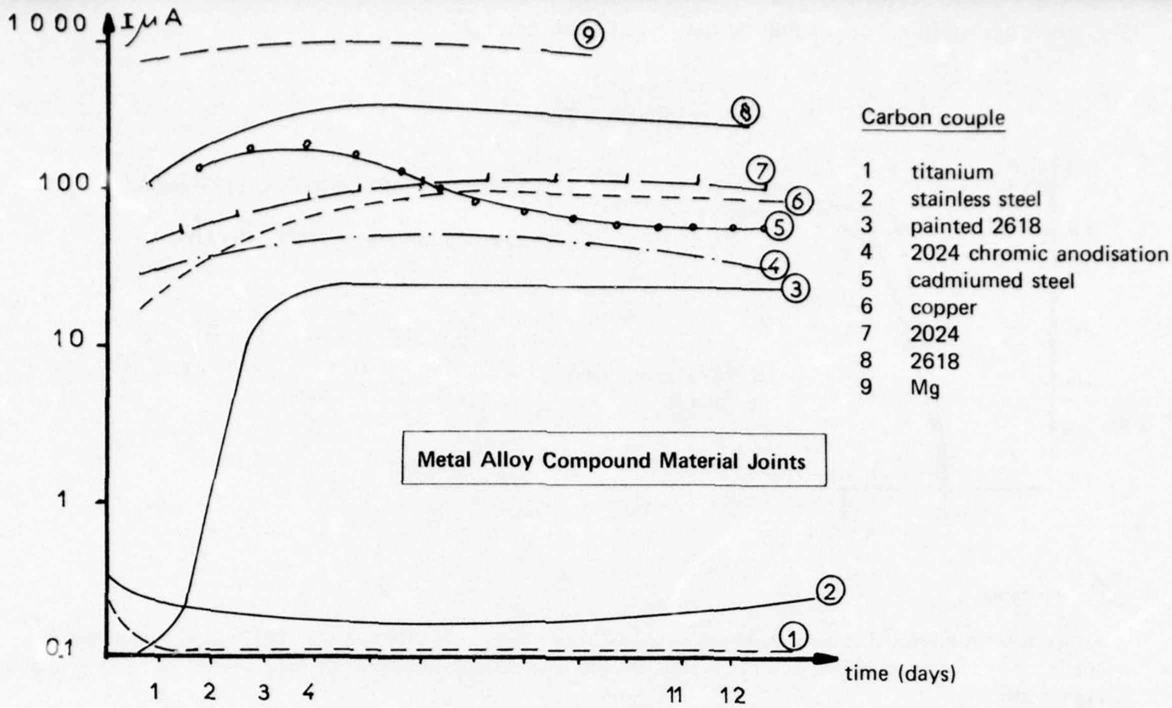


Influence of coupling with a different material

In badly designed joints, galvanic couples are responsible for major deterioration. It is customary to classify materials according to their free potential in a corrosive solution (corrosion potential), and to consider the gravity of galvanic coupling between two materials as depending on potential difference.

This evaluation is inadequate. It is preferable to consider the problem in terms of corrosion current, which is directly measurable in this particular case.

Current can be measured without interfering with the circuit, using a nil resistance ammeter. Correlation between these measurements and weight loss has been studied in detail by F.Mansfeld[4]. We have used this technique for the selection of links with compound fibre structures.



Influence of metallurgical structure

In the case of an alloy, corrosion in a humid medium is always due to the existence of anodic and cathodic zones, as with galvanic coupling of materials. These zones are microscopic – grain joints, defined compounds, matrix formation, etc. This is the case with the intergranular corrosion frequently encountered on sections in A-U4G1 ('2024), in state T4 (exfoliation corrosion).

This type of corrosion can be reproduced in the laboratory, using a cyclic acetic salt spray test. The cycle comprises:

45 minutes in salt spray at 35°C (5% NaCl pH 3 with $CH_3CO\,CH$)
120 minutes drying at 60°C
195 minutes water spray at 35°C.

In the case of sensitive materials, exfoliation appears in a few days.

We have attempted unsuccessfully to apply this test to the study of materials protected by paint. In this particular case, exfoliation can be reproduced by an alternate immersion/extraction test:

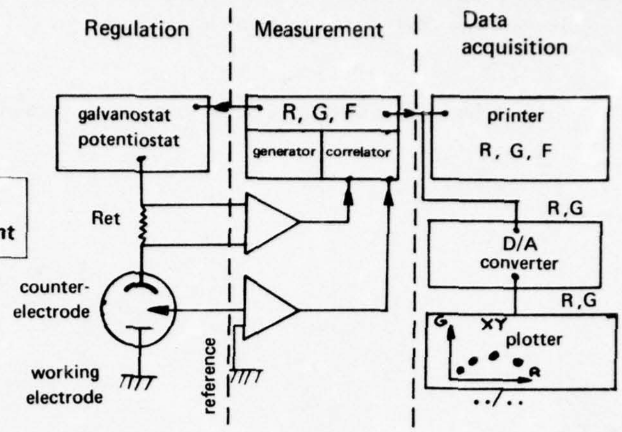
- immersion: 2 hours in 3% NaCl solution (pH 8)
- extraction: 2 hours at 35°C, RH 80 – 98%.
  temperature 35°C

The types of paint applied to sensitive alloys are thus selected by this test, limited to a period of 1500 hours. No corrosion must be traceable on the test-piece, on which a cross is scratched down to the metal, prior to the test. Slight pitting, not exceeding a distance of 1 mm from the scratches, is admissible. This corrosion is due to the existence of micro-sources, and it is not therefore possible to obtain a direct measurement of corrosion current. As we have seen, we are obliged to use voltage/current curves, or impedance diagrams (Epelboin[5]).

The application of reactive impedance measurement to the study of corrosion has not yet been developed very far, but we have used this method successfully for checking the anodization of light alloys. Anodization quality is generally checked by salt spray testing. This test is lengthy and results are difficult to evaluate, and we have attempted to replace it by the impedance measurement method[6].

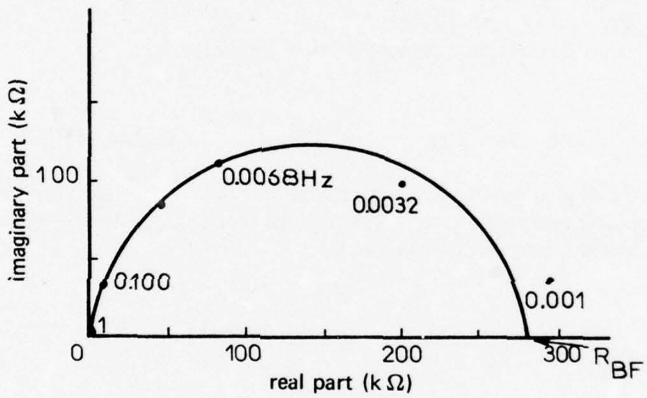
The anodized test-piece is placed in an electro-chemical cell with three electrodes, containing a solution of sodium chloride. Impedance is measured against frequency (10^4 to 10^{-3} Hz), using a frequency response analyzer.

Principle of Reactive Impedance Measurement

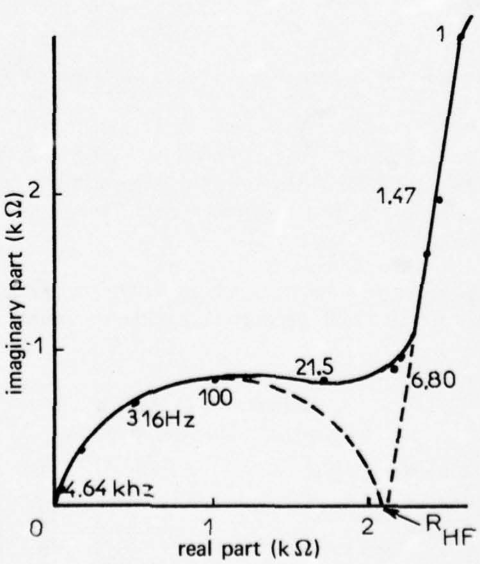


The impedance represented in the complex plane shows two capacitive arcs. It appears that at high frequencies, the arc is dependent on the nature of the protective layer, whilst at low frequencies impedance is a function of discontinuities in the protective film[6].

Impedance Diagram

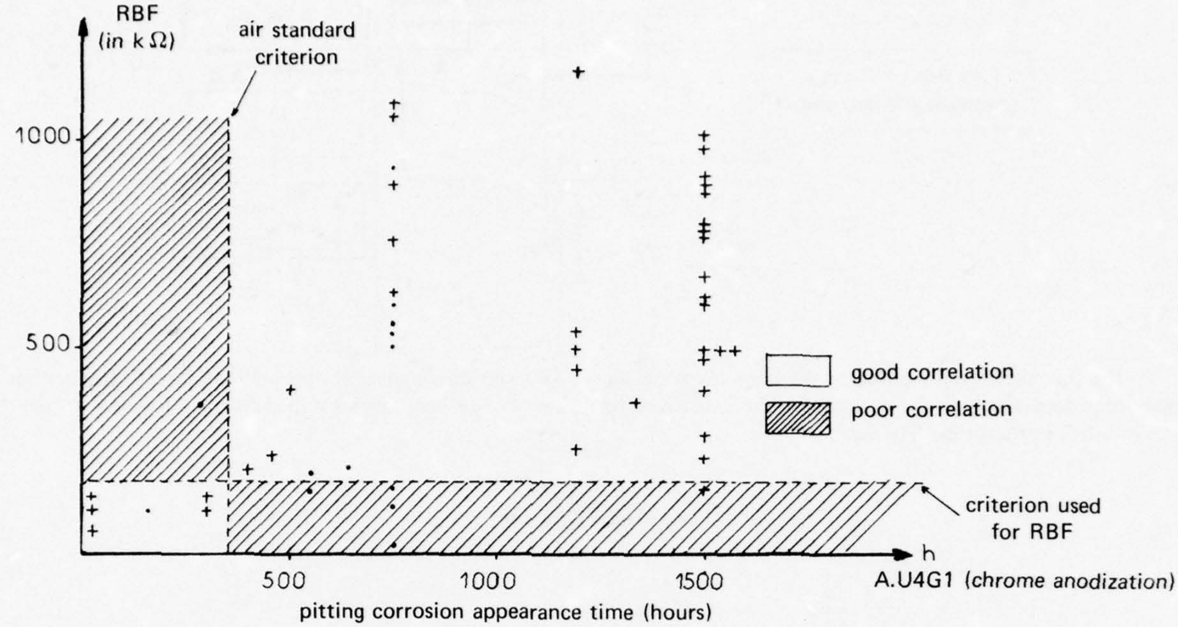


Anodized AU4G1 (medium: NaCl)



We found a close correlation between the dynameter of the LF arc (RBF) and resistance to salt spray.

Impedance/Corrosion Correlation in Salt Spray (5% NaCl)



This measurement is now fully automated, and could be easily adapted to the field of industrial control.

We have used a number of examples to demonstrate the possibilities of laboratory testing. These tests can be usefully applied simultaneously, and result data compared with that from prolonged testing in a natural environment (marine, industrial, and tropical corrosion stations, etc.).

5. CORROSION DETECTION

The detection of corrosion must also represent a basic preoccupation. Corrosion discovered prior to the propagation stage can be remedied easily. On the other hand, if propagation is advanced, repair will be difficult or even impossible.

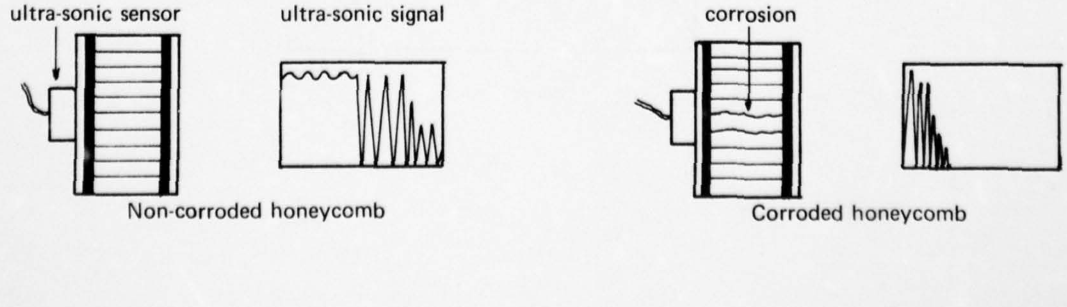
A – Initiation

Nature has helped us in our task, since corrosion is always accompanied by the formation of abundant oxides, acting as a clear indicator.

The start of corrosion is checked visually, using a magnifying glass, microscope, endoscope, etc., where necessary. All types of surface corrosion (pitting, filiform, etc.) can be traced in this way, on free surfaces. In the case of joints and other positions where access is difficult, corrosion can be traced by non-destructive test methods, such as radiographic, ultra-sonic, or eddy current.

For example, in a sandwich structure, detection of honeycomb corrosion in a light alloy can be achieved by the use of the "pulse echo" method. Careful calibration gives maximum contrast between the healthy and corroded parts.

Honeycomb Corrosion
Ultra-sonic detection method

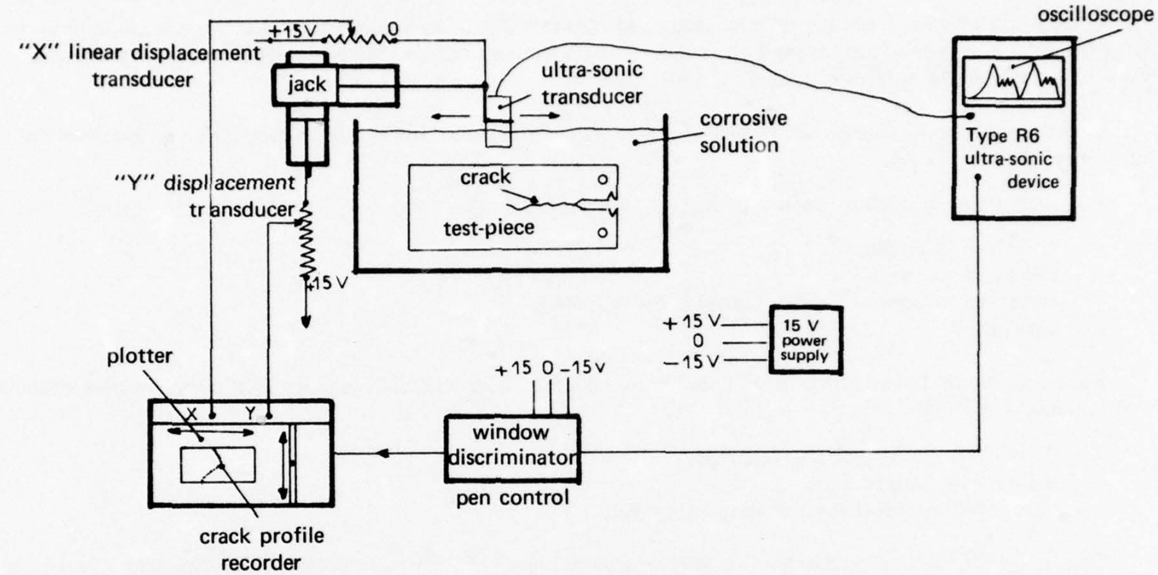


The presence of water can also be detected by ultra-sonic or, better still, radiographic methods.

B – **Propagation within the material**

Intergranular or transgranular propagation is more difficult to detect. Research type methods are used for detection of cracks (radiographic, ultra-sonic, eddy current, etc.). For example, a method has been developed in the laboratory for automatic crack monitoring on an SCC test-piece, using ultra-sonics.

Ultra-sonic Pneumatic Device for Monitoring Crack Progression



Measurement system

C – **Surface propagation**

This is the case, for example, with corrosion propagation in bonded joints. The exfoliation detection technique is used successfully in this context:

- sonic testing (light tapping on the surface under examination)
- sucker test (thin gauge sheets only)
- ultra-sonic testing
- sonic resonance test (Fokker bond tester, sonic resonator, coindoscope, sondicator, etc.)
- sonic eddy current methods (eddy current)
- holographic interferometer testing
- thermographic methods
- radiographic testing.

None of these methods can be considered of universal application. Choice of method depends on a number of parameters:

- minimum fault dimensions to be detected
- geometry of the part
- fault location (accessibility)
- material
- equipment availability
- cost
- ease of application.

In certain cases it is appropriate to use two different test methods, for clear detection and identification of suspected corrosion. In service, certain zones known to be subject to corrosion as a result of practical experience, are inspected at periodic intervals.

In the event of a major incident on an aircraft, a statistical check is carried out on other aircraft of the same type, to determine whether a systematic testing is necessary or not. In this way, frequent inspection and common

sense frequently lead to rapid detection of corrosion, thus avoiding excessively costly repairs and the risk of serious accidents.

6. CONCLUSION

This quick look at various test methods again demonstrates the diversity of corrosion study resources. The gradual application of scientific techniques is making the study of corrosion something other than a merely empirical science. However, experience acquired in various research laboratories will always be a valuable standby for the interpretation and forecasting of corrosion phenomena.

Comparison of a large number of test results and statistics will be necessary to avoid major misconceptions, in particular reference in the corrosion initiation phase, which we have not considered in detail in the present paper but which has been the subject of numerous and varied studies[7].

In the aeronautical industry, the choice of a material and its protection system is a compromise between the following:

- mechanical characteristics and mass $\left(\frac{R}{d}\text{, toughness, etc.}\right)$,
- resistance to fatigue,
- resistance to creep,
- resistance to corrosion (SCC, corrosion-fatigue, etc.),
- cost price.

For example, total insensitivity to SCC can be obtained on a structurally hardened light alloy, by over-annealing. This generally results in:

- drop-off in mechanical characteristics,
- reduction in fatigue limit,
- faster fatigue-corrosion crack propagation rate.

Thus in certain cases, a certain level of SCC sensitivity must be accepted in order to maintain other properties. However, a thorough knowledge of the risks involved, and efficient detection resources, are necessary. In this paper, we have considered some of the resources available to use in a selection of particular cases.

This list is far from exhaustive, since each new corrosion problem nearly always requires the development of a new test and special detection method. A final thought: prevention is better than cure, and all tests contribute to a substantial reduction in maintenance costs, whilst improving reliability.

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DESIGNING FOR CORROSION PREVENTION

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1.0 INTRODUCTION

To consider the problem implied by "designing for corrosion prevention" suggests an encyclopedic tour de force since we are concerned with aircraft in general and not with a specific component. Corrosion is to be prevented or minimized in a variety of components: heavy structural parts, skin, fasteners, avionics, hydraulic lines, pumps, engine components (including blades, burners, gears, etc.), windows, gaskets, etc. Further, the alloys utilized on aircraft include a broad range available in normal commerce but with emphasis on the light weight materials. Further, to be useful we must consider the type of corrosion and the range of circumstances to which the alloys are exposed.

This discussion avoids the encyclopedic approach and focuses on some specific and useful concepts. Some of the preventive ideas are quite simple and can be summarized as follows:

1. Prevent water from staying in contact with materials of construction any longer than necessary.
2. Avoid chlorides.
3. Avoid crevices.
4. Avoid high surface stresses.
5. Avoid hydrogen in metals.
6. Avoid defects which increase the stress intensity above K_{th} for fatigue or $K_{I_{scc}}$ for SCC.
7. Use chromium and/or aluminum in materials which get hot.
8. Keep K_{I_c}, $K_{I_{scc}}$, and K_{th} as high as possible.
9. Facilitate inspectability.

An important point of view in this discussion is that deterioration processes are an implicit part of nature--for engineering structures as well as in living systems. Thus, rather than avoiding the problem or backhandedly tolerating it, engineers must consciously acknowledge the inevitability of its laws and incorporate allowances into designs.

Another point of view which must be accepted is that aircraft are designed on the basis of cyclic loading, i.e. fatigue. Virtually all deterioration processes must somehow be assessed in terms of their implications for fatigue--either its initiation or propagation. Naturally, the corrosion of avionics equipment is not always viewed from such a vantage point and much of engine design is dominated by creep properties.

Designing for corrosion prevention is prompted by a very clear incentive: Keep the life cycle cost--including capital and maintenance--as low as possible without compromising safety, reliability, or availability. These latter implications are in fact related clearly to economics since any diminution ultimately increases the life cycle cost. Further, owing to the very high labor costs associated with maintenance and the generally reduced accessibility of parts, any action to reduce corrosion damage is most economically incorporated into the initial design. This may be accomplished either by a direct preventive scheme or by arranging the design so that routine maintenance can be easily and confidently performed.

This discussion starts simultaneously from two points. The first: There is a great incentive to carry the maximum payload with the minimum structural weight. The second: All engineering materials are chemically and mechanically unstable. Unfortunately, these produce opposing trends, i.e., while the former demands increasing the load carrying efficiency, the latter decreases it; materials which are used to achieve light weight structures tend to be susceptible to premature failure either for chemical, mechanical, or chemical-mechanical reasons.

The first point requires the use of high strength, light weight, and heterogeneous materials systems. Unfortunately, implicit in the use of high strength materials is a lowered critical stress intensity (K_{I_c}); concomitantly, the stress corrosion cracking

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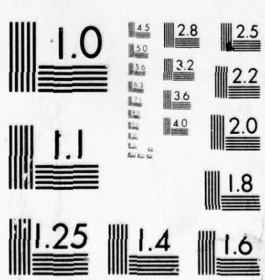

MICROCOPY RESOLUTION TEST CHART
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threshold ($K_{I_{scc}}$) is usually lowered. Also, the high strength materials are usually more metallographically heterogeneous; and such local heterogenities provide special sites for initiating fracture and accelerated corrosion processes.

The goal for light weight also leads to thin cross sections which are more easily perforated. For example, a pit which may develop in a thick section may eventually be stifled whereas the same pit would completely perforate a thin section.

Finally, the desire to optimize materials to achieve light weight gives heterogeneous materials systems intimate juxtaposition. Such heterogeneous materials systems are often susceptible to accelerated corrosion. For example, aluminum-graphite composite materials are readily attacked since graphite is an excellent cathode; cadmium coatings have been shown to cause the stress corrosion cracking of adjacent titanium parts.

With respect to the second point, the light weight engineering alloys--aluminum, titanium, and magnesium--are also extremely reactive chemically. These materials, in fact, are sufficiently reactive that they can be used as fuels for solid rocket motors. Serious and fatal fires have occurred when finely divided scraps or powders of these materials have ignited. While this high reactivity does not follow necessarily from their high strength or their lightness, it does, on the other hand, substantially increase the need for careful attention to measures for preventing corrosion. Pitting and stress corrosion cracks in these light weight materials can propagate as rapidly as 1-10 cm/hr under apparently innocuous conditions at room temperature.

Specific factors in the light or high strength aircraft materials which aggravate the chemical-mechanical instabilities are the following:

1. Low standard potential relative to the hydrogen and the oxygen electrode reactions. The values for standard potentials at room temperature are compared in Table 1.1.

2. Extreme thinness of the protective product layer film. This layer on structural materials is often as thin as 50 Å. This is a small dimension relative to the height of slip steps on the surface.

3. Broad range of loading circumstances in aircraft together with already existing residual stresses.

4. Higher triaxial stresses at crack tips in high strength materials. This attracts species such as hydrogen which reduce strength of metal-metal bonds and also promotes cleavage.

5. Relatively large volumes of some corrosion products which accentuate damage e.g. exfoliation.

6. Other features of chemical reactivity which accelerate failure: high solubility of oxygen and nitrogen in titanium; hydrides in titanium, high hydrogen diffusity in steel.

7. The substantially accelerating effect which the ubiquitous chloride ions produce in virtually all alloys. These effects are heightened by readily available oxygen.

8. Sensitivity of alloys to SCC by cadmium and mercury environments.

9. Accelerating effects of sulfur in jet fuels on deterioration of turbine blades.

TABLE 1.1

Standard Potential of Common Structural Elements. From Pourbaix (1).

Element	Standard Potential (volts)
Cu	+0.34
H_2	0.0
Ni	-0.25
Fe	-0.44
Cr	-0.91
Ti	-1.63
Al	-1.7
Be	-1.85
Mg	-2.36

Most of the preventive activities are incited by one of the reasons cited above.

To emphasize here a point of view which epitomizes the foregoing discussion: The reason for both pointing out and laboriously emphasizing the inherent chemical-mechanical instability of the materials used in aircraft is that they are in a dynamic balance with the environment. Decay of metals is a fact of life; dynamic deterioration must be met with an equally dynamic preventive program which is fully cognizant of the thermodynamic pressure for return to more stable--but less structurally useful--reaction products.

The design of aircraft, as in the design of any other engineering device, balances a set of desired performance objectives with the mechanical capacities of available materials subject to modifications imposed by environmental influences. Environmentally imposed reductions of load carrying properties are recouped to some extent by preventive measures. The design itself produces destructive environments such as surface heating, operating stresses, fuel chemistry. Other environments are generally exterior and devolve from the varying ambients in which the aircraft is required to perform.

In order to connect failures involving corrosion processes with design action, a distinction needs to be drawn between the mode of failure and the cause of failure. The mode of failure involves the process by which the failure occurs. This may be pitting, exfoliation, stress corrosion, etc. The cause is defined as that which can be fixed. Thus, the mode of failure may be exfoliation but the cause may be the lack of sufficient inhibitive compound in the rivet hole. The mode may be fatigue but the cause may be improper heat treatment or a too small radius. Shah (2) has analyzed failures from the vantage of Civil Aeronautics in Canada with respect to cause and mode for fixed-wing light aircraft and helicopter components. Table 1.2 summarizes failures according to mode and cause. The cause in this case has been assigned to those actions related to operating circumstances or to design.

TABLE 1.2

Summary of Failures - Components and Types (1966-70). From Shah (2).

	Number of Failures Based on Failure Mode					Number of Failures Based on Assigned Cause					
Type of Component	Fatigue	Overload	Corrosion, stress corrosion, hydrogen embrittlement	Excessive wear, deformation	Miscellaneous; high temperatures, galling, etc.	Improper maintenance, repair or O/H and inspections	Inadequate design or maintenance instructions	Manufacturing deficiencies	Abnormal operation or service damage	Undetermined	Total by Component
Powerplant	69	12	-	11	17	42	22	9	27	9	109
Landing Gear	30	58	5	-	2	20	22	3	45	9	95
Main Rotor Assembly	13	9	-	-	1	6	7	2	7	-	23
Propeller Assembly	16	3	-	1	1	17	-	8	4	10	21
Structural Members and Flight Controls	4	11	3	-	5	2	4	2	13	-	21
Tail Rotor Assembly	7	6	1	-	4	4	6	2	5	1	18
Miscellaneous Parts	1	5	-	-	2	-	1	1	6	-	8
Total by Type	140	104	9	12	30	91	62	25	107	10	295

Shah's table indicates another trend. The relatively large number of fatigue failures may be misleading. Some of these are initiated by corrosion processes, and the assigned mode of fatigue may not be correct. Leak (3) has noted that what ends up as being called fatigue may have been initiated by corrosion. He notes two failures costing \$6 and 12 million respectively where the fatigue mode was initiated by corrosion pits.

Another view of failure modes has been published by Speidel (4) as shown in Figure 1.1. Here, data from 3000 failure reports were analyzed to determine the occurrence of stress corrosion failures involving various alloys. These reports were taken from six aerospace companies and a number of government agencies and research laboratories in the US and five countries in Western Europe. These statistics vary from those of Shah (2) in that SCC is a higher fraction of failures. However, the primary value to be served here is to note that SCC as well as fatigue is a major mode of failure. Speidel further reviewed the sites for initiating the cracks as well as the type of these. These are summarized in Tables 1.3 and 1.4. Noteworthy in Table 1.4 is the high frequency of initiation of SCC failures caused by residual stresses.

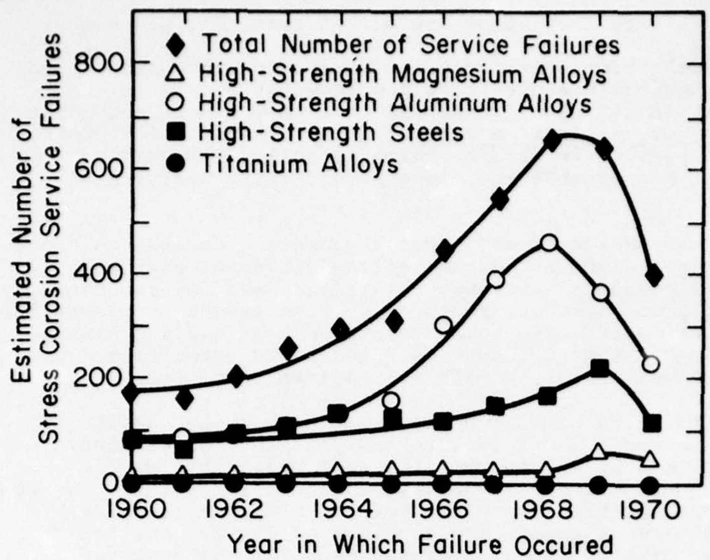


Figure 1.1. Estimated number of stress corrosion service failures of aerospace products in Western Europe and North America from 1960 to 1970. From Speidel (4).

TABLE 1.3

Initiation Sites of Stress-Corrosion Cracks in High-Strength Aluminum Alloys From Speidel (4)

	Percent
Stress raisers due to design (bore hole, sharp radius, etc.)	25
Holes for interference fit bushings	15
Corrosion pits	12
Fatigue cracks	5
Galling, fretting, wear	5
Intergranular corrosion, exfoliation	4
Not known	34

TABLE 1.4

Sources of Stresses Causing Propagation of Stress Corrosion Cracks in High-Strength Aluminum Alloys. From Speidel (4)

	Percent
Residual stresses (from heat treatment and fabrication)	40
Installation stresses (fit-up stresses, improper shimming, torque)	25
Service stresses (amplified due to stress raisers)	25
Not known	10

2.0 ENVIRONMENTAL INFLUENCES

2.1 Introduction

Selecting alloys and preventive schemes depend upon the environmental circumstances which aircraft experience. Designing for preventing corrosion depends upon a precise definition of the environment over the full range of circumstances to which the aircraft is to be exposed. Defining these environments must include both the adventitious as well as more usually expected environments. This section defines the environmental dimensions in which materials should perform and which must be considered in design. A typical set of environmental conditions which must be endured is listed in Table 2.1 from the requirements for the B-1 program.

TABLE 2.1

Environmental Conditions to be Sustained in the B-1 Program

- All-Weather (MIL-STD-210)
  - Rain, Snow
  - 1 - 100% RH
  - Salt Spray, Industrial Pollutants
  - Sand, Dust
  - Abrasion (Takeoff, Landing)
  - Fuel, Hydraulic Oil, Coolants, Sealants (Including Spillage)
  - Sunlight, High Altitude UV
  - Ground Temp. -65° to 125°F
  - Short Storage: -80° to 160°F (203° F Cockpit)
- Flight Temperatures (Typical High) 265°F 390 Hrs
- Peak Temperatures
- Life 15 - 20 Years

In this discussion of environments I am taking a broad view. Identifying environments for design should be based upon the following three ideas:

1. The environment includes all chemical species to which structural materials are exposed whether they are the obvious standard ones or are possibly adventitious ones which, á la Murphy's Law, may reasonably contact the structure. Such standard and non-standard species can arise in the atmosphere, thermal insulation, welding flux, hydraulic fluids, sealants, etc.

2. A proper statement of the environment includes the temperature and stress with their complex time dependencies in addition to the chemical species. The effects of most chemical species are sensitive to and often greatly exacerbated by increasing temperature as well as both static and cyclic loads.

3. Defining the environment and organizing preventive procedures applies at all stages in the life of an aircraft including: manufacture, testing, storage, shipping, in flight operation, between flights on the ground, and repair availabilities. Failures can, and do, occur during any of these regimes of time. This idea I call the "Total Environment Concept."

In approaching a detailed consideration of designing for corrosion prevention, I have proposed a schematic corrosion correlation equation. I have also discussed the "Total Environment Concept" further in section 2.3.

2.2 The General Environmental Equation

Corrosion processes are complex in their dependence upon alloy composition, environmental composition, environmental concentrations, physical arrangements, temperature, stress, etc. Developing definitive rate laws is difficult enough for simple static systems where the metal and environments are well defined. Presuming to develop a general quantitative equation for an engineering system, exposed to environments which are not well defined, stretches unreasonably the state of analysis. Nonetheless, in this case a useful purpose is served by developing a very general relationship which indicates general trends within a chemical-metallurgical framework. Equation (1) is the result of such an effort to develop a general view of corrosion problems in aircraft applications.

$$(T)(1 + C)\left(\frac{1}{1 + I}\right)(1 + H)(1 + L)(1 + S)(1 + P)(t) = A \qquad (1)$$

The quantity A represents total penetration into the metal at some time. Clearly the detailed functional form is qualitative. There are no exponents nor coefficients. The multiplicative arrangement--as opposed to additive--implies the interdependence of corrosion processes.

The use of the (1 + X) form means that when X is null the attack does not go to zero. Further, all the X quantities are taken qualitatively as positive implying an increase in magnitude, circumstances, or severity. A negative stress here is null.

The constituents of equation (1) are defined below.

(T) is the temperature. Virtually all the degradation processes of interest are accelerated by increasing temperature. This dependence does not apply to all metal environment systems. For example, Williams and Nelson (5) showed that the velocity of SCC in high strength steel exposed to hydrogen increases exponentially below room temperature and reverses this dependency above. However, the direct temperature dependence is broadly enough applicable that it can be left as is.

(C) refers to chemical species. The magnitude of C corresponds to both the aggressiveness of the species as well as its concentration. This term is given as (1 + C) since pure water itself is aggressive and can support SCC crack propagation.

(H) is the concentration of water as in hydraulic fluid or the relative humidity. Most corrosion reactions of interest occur in the presence of water. Rarely are there anhydrous circumstances where corrosion of aircraft materials occurs. The term is given as (1 + H) since some non-water-containing environments accelerate corrosion: e.g. this is the case for the SCC of high strength steels in hydrogen-containing environments such as HCl, HBr, and H_2S. Also, for the hot corrosion in turbine blades the key accelerating species seems to be molten sulfate.

(I) refers to inhibitive species which are added intentionally such as chromate used for wet rivets. The dependence is given as $(\frac{1}{1 + I})$ since inhibitors are not always used and since increasing the inhibitors generally decreases the corrosion attack.

(L) refers to light which, especially as ultraviolet, accelerates the embrittlement of polymeric solids. Certain corrosion reactions are also accelerated by light but these are usually not significant for metals. Light produces a secondary influence in that the hot sun accelerates drying and consequent local concentration of possibly aggressive chemicals.

(S) refers to the stress and is given as (1 + S) since corrosion proceeds readily without stress. However, stress accelerates many forms of corrosion such as general attack and pitting. Usually, stress exerts its greatest effects on stress corrosion cracking and corrosion fatigue.

(P) refers to the physical aspects of the environment and includes physical features associated with erosion, cavitation, galvanic cells and crevices.

(t), the time function, includes the time required to achieve more aggressive conditions as well as the time over which corrosion reactions proceed.

This eight factor equation is naturally imprecise in detail and would require different functional dependencies for different alloys and modes of corrosion. However, it provides a useful means for checking on the critical factors which contribute to corrosion processes. Sections 2.5 through 2.10 consider important components of the equations as they apply to the various modes of corrosion.

2.3 Designing for Corrosion Prevention

Designing for many of the forms of corrosion is not performed on the same apparently quantitative basis as is structural design. But even structural design lacks precision owing to uncertainties in the loading spectrum, the effect of mechanical and corroded surface conditions on fatigue initiation, and on the complex interactions of a large structure.

Corrosion design is based generally on two types of testing. General attack, pitting and crevice attack, the effects of alloy composition, coatings, joint design, fastener configurations, and environmental compositions are evaluated using a variety of corrosion tests which involve, usually, measuring the extent of attack over some time period. Evaluations are performed visually, metallographically, and by weight change. Configurations which survive the test conditions and which give better performance than previous tests which already have established correspondence with flight experience are presumed to be capable of longer life. Such assumptions are usually reasonable.

To restate this mode of testing: experience in the field indicates that failures are occurring earlier than desired; a test program is started to develop a better scheme; and resulting systems from new tests become the new corrosion preventing system.

While the approach described above is not precisely predictive, it works and has been accepted by the aircraft industry.

The second type of corrosion testing for developing design bases for preventing corrosion is associated with stress corrosion cracking (SCC) and corrosion fatigue (CF). Here the nature of testing depends on whether initiation or propagation are critical. For determining initiation controlled processes an endurance limit type of curve is determined for both stress corrosion cracking and fatigue. Such a plot for aluminum is shown in Figure 2.1. These data provides the basis for using sheets of high strength aluminum alloys with impunity in the longitudinal direction.

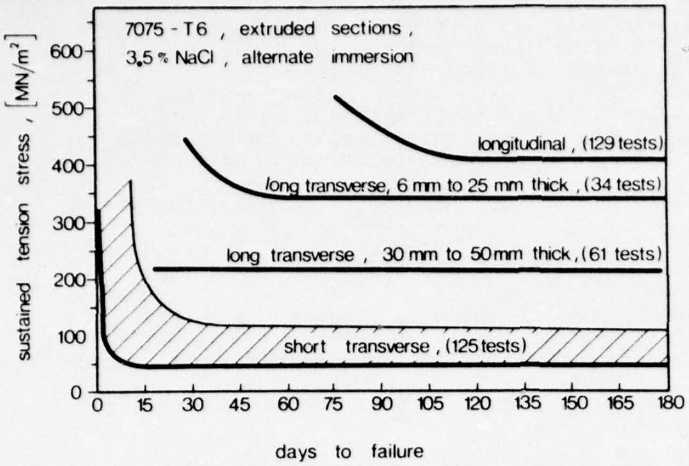


Figure 2.1. Smooth-specimen stress corrosion test results for 7075-T6 extruded sections, illustrating the effect of specimen orientation on time to failure and threshold stress. Scatterband for short transverse specimens, bottom of scatterband for long transverse and longitudinal orientations. Based on data in reference 6.

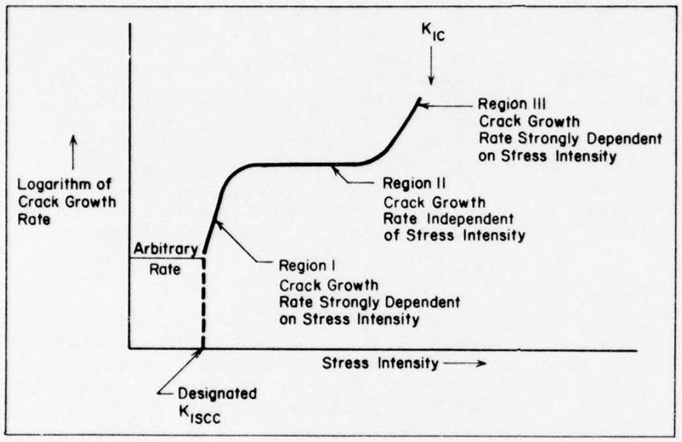
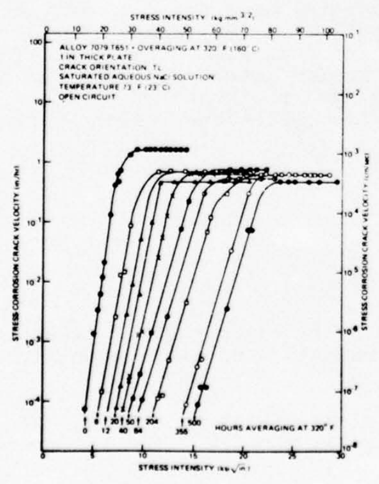


Figure 2.2. Schematic representation of stress corrosion data produced by test method based on crack growth rate. From Brown (7).



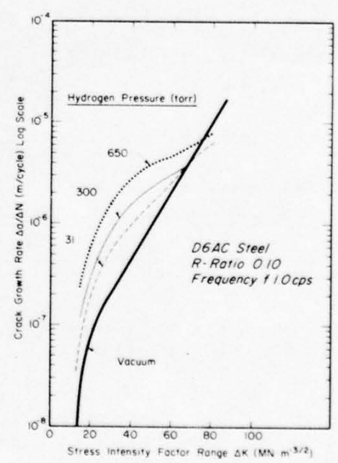


Figure 2.3. Effect of overaging on the on the velocity of stress corrosion cracks in alloy 7079 immersed in NaCl solution. From Speidel (8).

Figure 2.4. Cyclic crack growth rate as a function of hydrogen gas pressure. From Skogsberg (9).

For the case of propagation in SCC and CF the crack extension is measured as a function of time or number of cycles. The data are plotted as crack velocity vs. stress intensity at the crack tip for SCC or as crack growth rate, da/dn, (a = crack depth, n = number of cycles) vs. ΔK (the range of stress intensity).

A schematic plot for stress corrosion crack velocities in SCC is shown in Figure 2.2. Here the designer is interested in three quantities: the threshold for the onset of SCC, $K_{I_{scc}}$; the plateau crack velocity; and the critical stress intensity K_{I_c}. $K_{I_{scc}}$ tells the designer minimum conditions for propagating cracks; the plateau crack velocity tells the designer what is the maximum crack length which will exist after some exposure time. An example of experimental results is shown in Figure 2.3.

In fatigue the da/dn vs. ΔK information can be used to predict the extension of cracks between inspection periods. The threshold for the propagation of corrosion fatigue cracks, K_{th}, is often lower than $K_{I_{scc}}$ and the designer is then constrained to use such a value. Figure 2.4 shows an example of such a da/dn vs. ΔK plot for corrosion fatigue.

While the two types of testing discussed above, the exposure tests and the mechanical-chemical tests, vary in their precision and quantitative bases for predictability, they have, nonetheless, served effectively. An equally important but uncertain area involves improving the characterization of the operating chemical and mechanical conditions. This area needs more attention.

Designing to prevent corrosion has deeper roots which underlie the above. I have already noted that engineering materials are inherently unstable, and they derive their stability from thin protective films of insoluble reaction products. The regimes of stability of these predictive films as well as the regimes of solubility--where the soluble ions are more stable than the films--are summarized on plots of the pH and electrochemical potential such as the one for iron in Figure 2.5. Here the various equilibria and regimes of stability are shown. Also the environmental equilibria involving the reductions of water to hydrogen and the reduction of oxygen to water

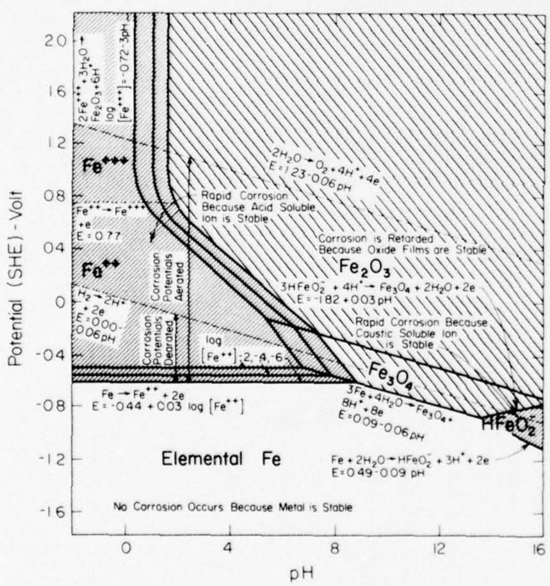


Figure 2.5. Annotated potential-pH diagram for the iron-water system at 25°C. The hatched regions indicate zones of various reaction types: no hatching indicates that the metal will not corrode; fine hatching means that the metal tends to corrode since the ionic species are soluble; broad hatching shows regions of insoluble product layers where passivity should occur if the layers are protective. The applicable equilibria with their corresponding pH and potential dependencies are placed parallel to the respective lines. Regions are also noted where the corrosion potential can exist depending upon the state of aeration of aqueous solutions. From Pourbaix (1).

are shown. Corrosion will occur, as noted in Figure 2.5, in the ranges of potential between the oxidation equilibria of the metal and the reduction of environmental species.

For aluminum the correlation of the potential pH diagram with solubility and corrosion rate is summarized in Figure 2.6. The diagram at the top gives the regimes of thermodynamic stability; and the direct measurements of corrosion rate and solubility follow this prediction.

Thus, in designing for preventing corrosion these diagrams are useful in predicting the regimes of oxidizing conditions and pH where corrosion is to be expected. Similar diagrams for other important aerospace materials are summarized in Figure 2.7. Here the regimes of passivity and solubility are distinguished. The metals Ti, Al, Mg, Be, and Fe are the primary structural materials of the aerospace industry. Titanium is noteworthy for the very broad range of stability of its protective film. The

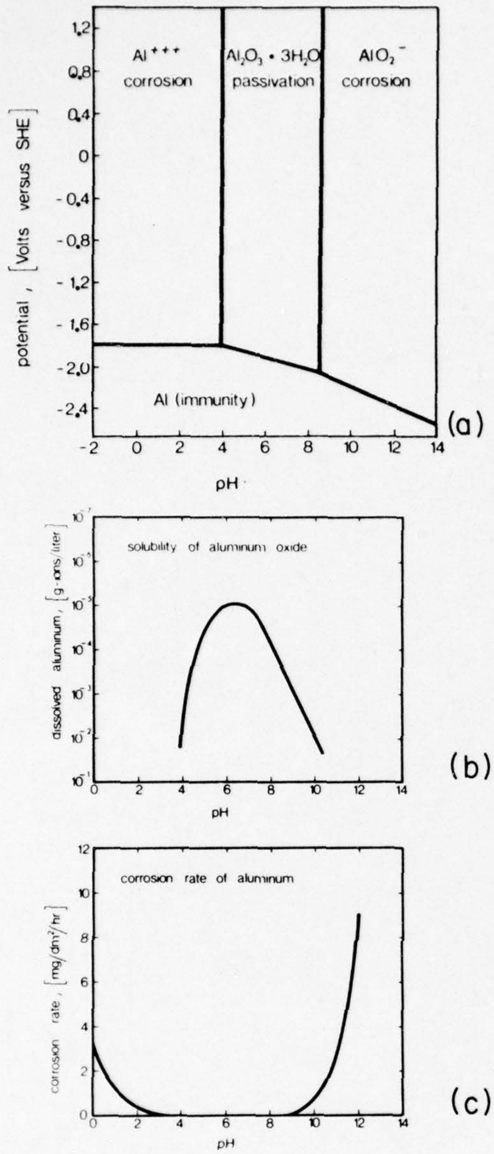


Figure 2.6. Relationship between potential-pH diagram for aluminum (a), the solubility of aluminum as affected by pH (b), and the corrosion rate (c). All data at room temperature. Adapted by Speidel (10). From Deltombe, Magistad, and Shatalov.

fragility of magnesium in environments is readily rationalized by the broad range of solubility of its ions. Chromium is interesting to aircraft design both because of its use as a plating and as the chromate inhibitor. In both cases the protective result is a broadly stable Cr_2O_3. The plating produces this on its surface and the soluble chromate ion is reduced to form the insoluble oxide precipitate. The corrodibility of zinc and cadmium result from the relatively broad range of solubility of their ions.

Simply, the diagrams of Figures 2.5, 2.6, and 2.7 provide the essential bases for all corrosion prevention. With these as a basis other testing for rates or for the behavior of complex materials systems takes on a systematic significance.

The thermodynamic approach outlined above then must be modified to take into account the effects of aggressive ions such as halides. These effects are usually investigated using electrochemical measurements where the corrosion rate in terms of reaction current is determined as a function of the applied potential. When the current increases very rapidly a breakdown in the protective capacity of the film is significant. The potential at which this breakdown occurs is called the pitting potential since this corresponds to the morphology of attack above this critical potential. Figure 2.8 summarizes important properties associated with the dependence

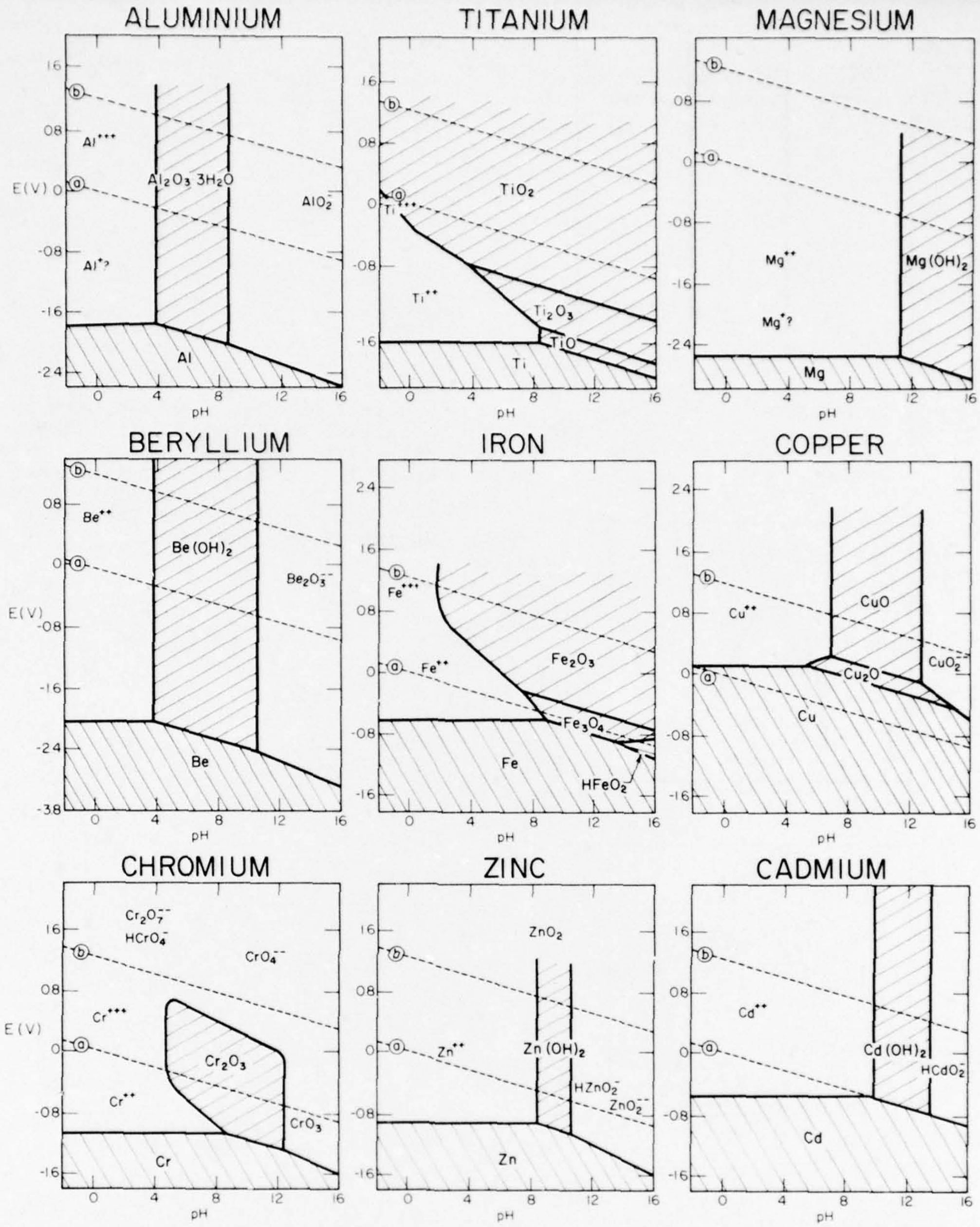


Figure 2.7. Potential-pH diagrams for metallic elements used in aerospace alloys.

of pitting of aluminum and its alloys.

The development of alloys and the interpretation of more complex corrosion experiments relies on electrochemical information of the type in Figure 2.8.

2.4 The Total Time Concept

The anticipated service environment is often--in fact usually always--the only one considered when assessing the stability of engineering materials. On the contrary, failures of aircraft are well known to have occurred before they leave the manufacturing areas or during shipment or storage. If an obvious failure has not already occurred during these stages, which are preliminary or intermediate to operation, the incipient nuclei are often there. These nuclei may be either associated with unremoved contamination or with already initiated defects from pitting or stress corrosion cracking.

Designing for the environments sustained in each state in an aircraft's life cycle can be organized systematically. The procedure involves identifying explicitly each of the stages in the life of an aircraft and subsequently defining the associated environments. Each of these environmental sets is then considered with respect to the potential damage; and thereupon preventive or ameliorative action is taken.

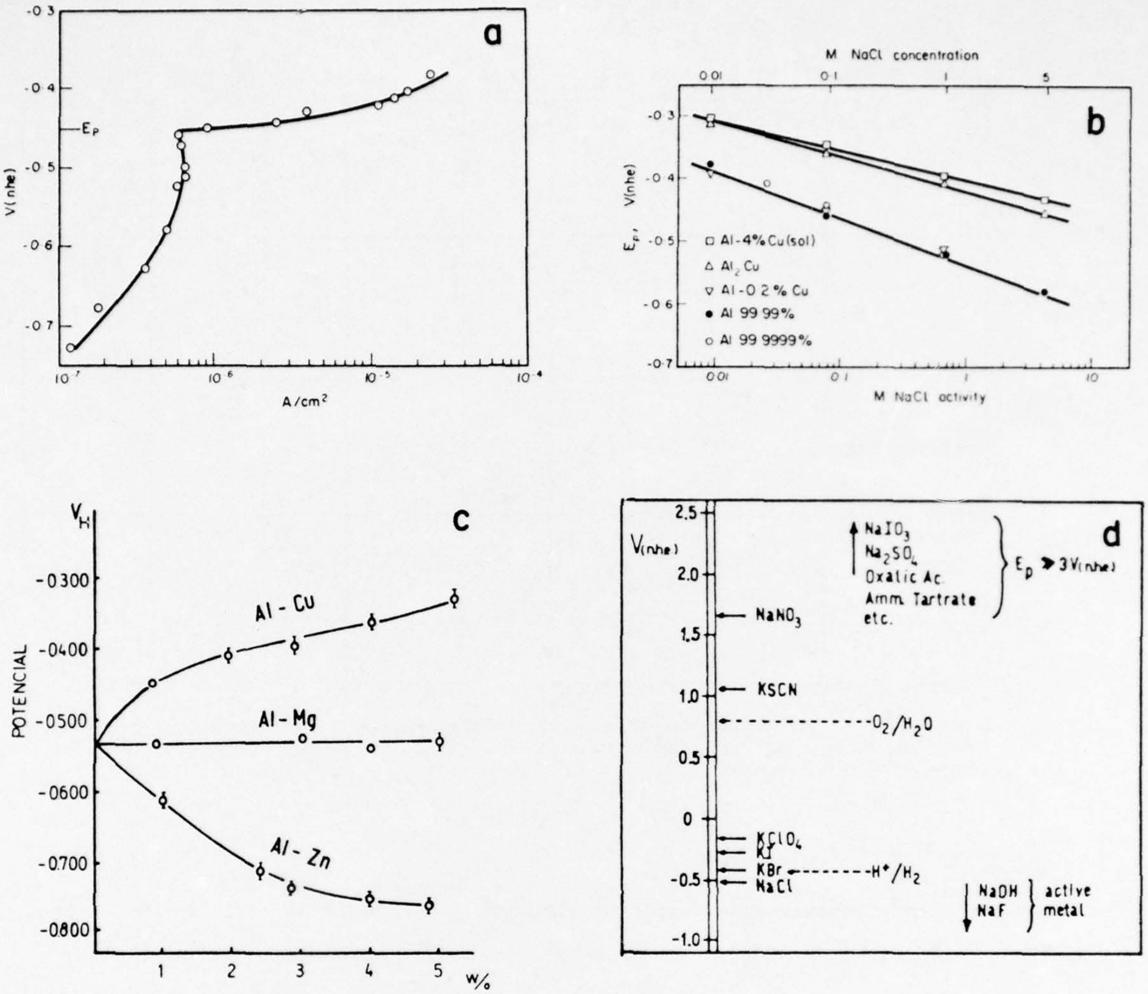


Figure 2.8. (a) Anodic polarization curve of 99.99% Al in deaerated 0.1M NaCl solution. (b) Effect of the chloride concentration on the pitting potential of pure aluminum and various Al-Cu alloys in deaerated NaCl solutions. (c) Effect of alloying elements on the pitting potential of binary aluminum alloys. (d) Comparison of the pitting potentials of Al in various electrolytes. From refs. 13, 14, 15.

Corrosion induced failures of aircraft during these non-operational circumstances are too frequent to be neglected and an orderly approach to preventing them should be organized. The components of equation 1 can be utilized as a checklist for each of these time regimes.

Figure 2.9 shows an example of a chart which can be used for assessing the advance of stress corrosion cracks in a structure according to the various time regimes. The chart asks the question of the simultaneous presence of stress and environment. If the stress exists but no environment, or vice versa, cracks will not advance. If both exist then crack advance is possible and will accumulate from stage to stage.

The chart of Figure 2.9 also identifies the fact that ameliorative action could be taken at each of these stages and requires the designer to define preventive action. While this chart is qualitative it, nonetheless, provides a systematic framework which could be followed for SCC phenomena as well as being applied to other corrosion phenomena.

TOTAL ENVIRONMENT

	FABRICATION	TEST	PACKAGE	SHIP	STORE	INSTALL	TEST	OPERATE	SHUT DOWN
STRESS									
ENVIRONMENT									
DAMAGE EXTENT (CRACK LENGTH)									
CORRECTIVE ACTION									

Figure 2.9. Schematic table for arrangement of data during time regimes where interacting conditions can be assessed for possible initiation and propagation of damage.

2.5 Temperature (T)

Temperature and temperature changes in aircraft are associated with the following.

1. From the ground to high altitude involves changes of perhaps +40 to -50°C.

2. In flight, surfaces suffer aerodynamic heating which increases with the speed. This becomes a critical problem with supersonic aircraft.

3. Aircraft are capable of flying such long distances that they may change ambients substantially at either end of the flight. Upper wing surface temperatures up to 108°C have been recorded in Arizona (17).

4. Naturally, the highest temperature occurs in the engines but high temperature alloys are used for these applications.

The dependence of corrosion reactions upon these temperatures varies depending on the mode. An example of region I and region II temperature dependence for the SCC of aluminum is shown in Figure 2.10. Here two different activation energies are shown for the two regions (4).

2.6 Chemical Composition (C)

The chemical compositions to which aircraft materials are exposed can be divided approximately into six groups. Each of these exert deleterious effects depending upon stresses, identity of the species, and the concentration of the environments.

Before itemizing the special environments an important modifying point should be made: while aggressive species often occur in low and apparently innocuous concentrations, these species can be readily concentrated in local regions. Probably the most important of these concentrating processes is wetting and drying. Sites in the aircraft structure where moisture can collect and evaporate and where this process may be repeated would be preferred locations for accelerated corrosion.

The categories of environments which need to be systematically considered are outlined in sections 2.6.1 to 2.6.5.

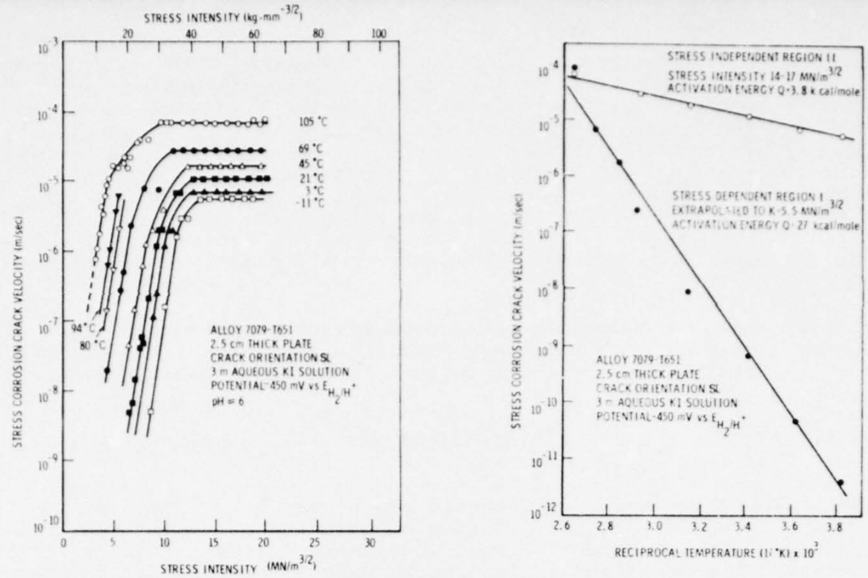


Figure 2.10. (a) Crack velocity vs. stress intensity for aluminum alloy 7079-T651. (b) Activation energies for regions I and II. From Speidel (4).

2.6.1 Normal Atmospheres

The most important atmospheric species are oxygen and water. Oxygen exerts its influence especially in localized corrosion processes such as pitting, SCC, and crevice attack by substantially accelerating the total cathodic reaction. Little can be done to prevent the effects of oxygen except to coat metals and minimize the available cathodic areas.

In addition to oxygen and water the atmosphere contains acid forming gases as pollutants: CO_2, SO_2, NO_x. These dissolve in water, hydrolyze, and produce acidification. Acidification accelerates general attack owing to the pH dependence of the stability of the oxide film; acidification also accelerates the entry of hydrogen.

Also, in the atmosphere NH_3 and H_2S may be present as a result of decaying vegatation. NH_3 is particularly aggressive to copper alloys and H_2S accelerates the entry of hydrogen into metal according to the well known poisoning effect.

A particularly corrosive environment occurs on the decks of aircraft carriers powered by fossil fuels. The soot deposits contain sulfate and chloride. Table 2.2 shows the pH and sulfate from the soot of four different aircraft carriers.

Near the sea coast or for carrier based aircraft, chloride is in the atmosphere and deposits readily. Chloride exerts its primary effect on accelerating the localized attack processes such as pitting, SCC, intergranular attack, and crevice corrosion. The influence of chloride on the localized attack of aluminum alloys was shown in Figure 2.8.

Finally, ozone, although present in small concentrations causes stress corrosion cracking of rubbers. This effect is usually counteracted by adding special agents to the rubber to prevent ozone cracking; but other uses of rubber may not always be so protected.

TABLE 2.2

Stack Soot Analysis. From Brown, Shaffer, and Goldberg (18)

Carrier	pH	$SO_4^=$
Bon Homme Richard	2.7	21%
Saratoga	2.8	33
Shangri-La	2.4	11
Forrestal	4.0	11

2.6.2 Normal Internal and Operating Environments

A second class of environments is those fluids associated with normal operation. By far the largest quantity of such fluid is the fuel. Here the importance of its chemistry depends upon whether we are interested in the fuel storage or the burning function. For the former the primary concerns are water and bacteria; the problem with both may be handled by lining the tanks or by removing such species. Spores of the fungus cladosporium resinae are often present in kerosene type fuels. These spores, especially at tropical temperatures, will produce fungal growth. These growths tend to activate in water globules but may be eradicated by using biocides (17).

Hydraulic fluids constitute another environment. The primary concern here is the presence of water.

Thermal insulation used to maintain cabin temperature constitutes a type of chemical environment. Here, any aggressive chemicals which are soluble can be leached by condensation or by water leaks. These solutions would accumulate on adjacent walls or at low points.

Other chemical environments may be associated with sealants, machining liquids, and lubricants.

Aircraft are periodically washed. These solutions may be slightly acidic or may be basic in the range of pH 10.5 to 12. Washing solutions are usually inhibited with silicate to prevent accelerated attack. These solutions, like the rain, will inevitably accumulate in crevice areas and their aggressiveness in such circumstances should be carefully evaluated.

Burning the fuel in engines produces sulfur compounds. Of the possible species which are produced, sulfur is the most virulent and contributes to the hot corrosion phenomenon. In hot corrosion the aggressive attack is best related to a molten sulfate environment adjacent to the metal surface (19, 20, 21). The stability of alloys may then be evaluated in molten sulfate environments. In fact, the thermodynamic stability diagram for aluminum in molten sulfate has the same characteristics as that for aluminum in aqueous solutions. Aluminum, as well as chromium, is widely used as an alloy addition to prevent the hot corrosion of nickel base alloys. A comparison of the two thermodynamic diagrams is shown in Figure 2.11. Results from corrosion tests of alloys with and without oxides shown to be stable in thermodynamic plots are shown in Figure 2.12. Here, the alloys which contain species (e.g. V, W, Mo) which change the sulfur activity to an unstable zone of Figure 2.11 b sustain accelerated corrosion.

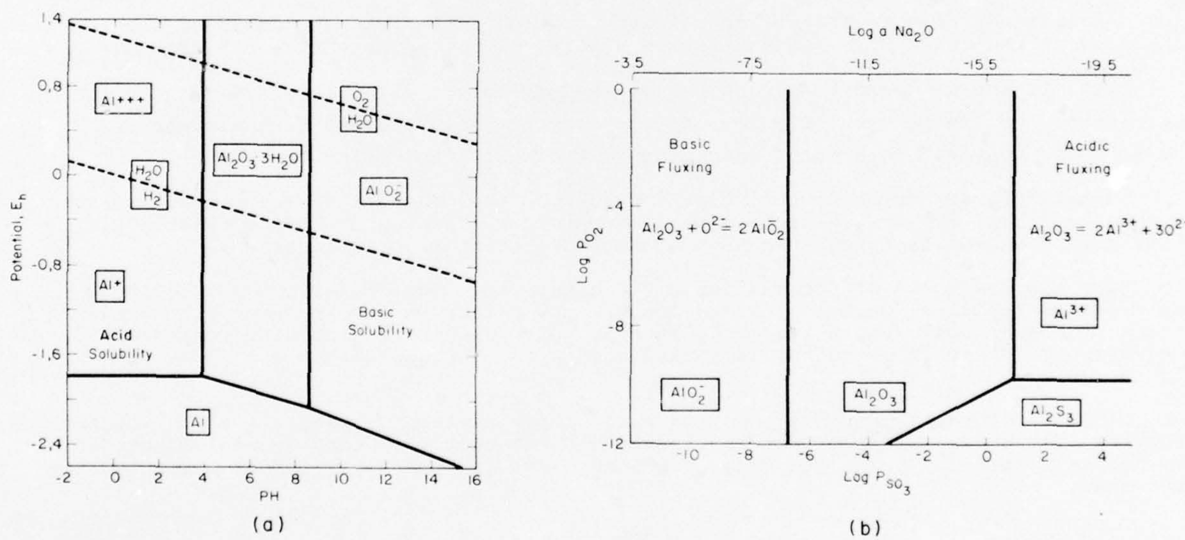


Figure 2.11. Comparison of thermodynamic diagrams of the stability of aluminum in water at left (a) and in molten sulfates at right (b). The water developed for 25°C and the other for 1000°C. The reversal in location of acid and basic regions arises from conventions in the respective technologies.

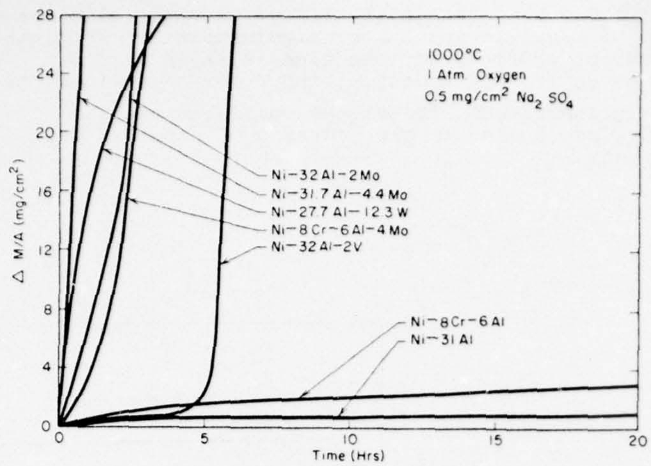


Figure 2.12. Weight change versus time for the oxidation of Na_2SO_4-coated (0.5 mg/an^2) specimen of Ni-Al and Ni-Cr-Al alloys as effected by the addition of V, Mo, and W. From reference 21.

2.6.3 Personal and Cargo Environments

Accelerated corrosion associated with toilet facilities is well known and is a major problem in aircraft carrying personnel. Similar but less severe problems are associated with food service facilities.

On cargo carrying aircraft, spillage of chemicals and excreta from animals have produced accelerated corrosion. Occasional spillages of mercury occur when thermometers or other mercury containing equipment is broken. Normally mercury is prohibited in aircraft owing to its accelerating effects in liquid metal cracking of aluminum alloys (23).

2.6.4 Protective Coatings

Electrical cables and electronic gear are insulated or protected. Sulfur and chlorine in some of these materials can be released upon heating. Polyvinyl chloride has been shown to be particularly liable to the release of HCl.

Cadmium, which is widely used as a protective coating on steels, is inimical to titanium and causes a type of SCC (24).

2.6.5 Manufacturing Environments

Manufacturing environments include cleaning solutions, machining lubricants, quality control such as dye penetrant and magnaglow, electroplating, welding fumes, etc. All of these should be carefully evaluated for the presence of pernicious species, e.g. electroplating solutions favor entry of hydrogen.

2.7 Humidity and Water (H)

Water is a critical species in the corrosion of engineering materials. Its contribution seems to arise principally for five reasons:

1. The reduction of water to hydrogen ($C + 2H_2O \rightarrow H_2 + OH^-$) is noble to most of the equilibria for aerospace materials as shown both in Table 1.1 and in Figures 2.5 and 2.6. Thus, water is a corrodent.

2. Water is an electrolyte and as such can dissolve relatively large quantities of ions depending, naturally, on the pH as shown in Figure 2. . This high solubility permits the substrate to corrode.

3. Water can be hydrolyzed to form acidic or basic solutions depending on the anions and cations. These variations in pH exert strong influences on the solubility of metals and oxides.

4. The hydrogen which results from the reduction of ions is well known to accelerate the stress corrosion cracking of high strength steel and titanium alloys. Also, hydrogen, which is produced in electroplating solutions as a result of the low potentials, produces various modes of hydrogen damage.

5. Water also produces protective films according to the half cell reaction:

$$M + H_2O = MO + 2H^+ + 2e$$

While this is sometimes beneficial, it may also be deleterious insofar as the electrochemical potential may be shifted into a regime where SCC is favored.

Relative humidity at fairly low values can sustain the SCC of aluminum alloys as shown in Figure 2.13. While the role of water in the SCC of aluminum is not completely clear, it clearly functions as a source of hydrogen for the high strength steels. Figure 2.14 from McIntyre (25) compares water, dry hydrogen, and H_2S showing that the plateau crack velocity is progressively increased. The stress corrosion cracking of titanium alloys in methanolic solutions depends on the presence of water as well as NaCl--both in relatively small amounts.

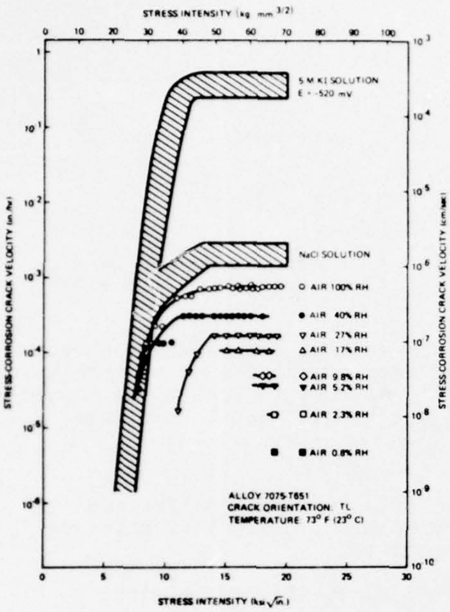


Figure 2.13. Effect of humidity and stress intensity on stress corrosion crack velocity in a 7075-T561 Al alloy. Results compared with crack propagation in NaCl and Ki solutions. From Speidel (8).

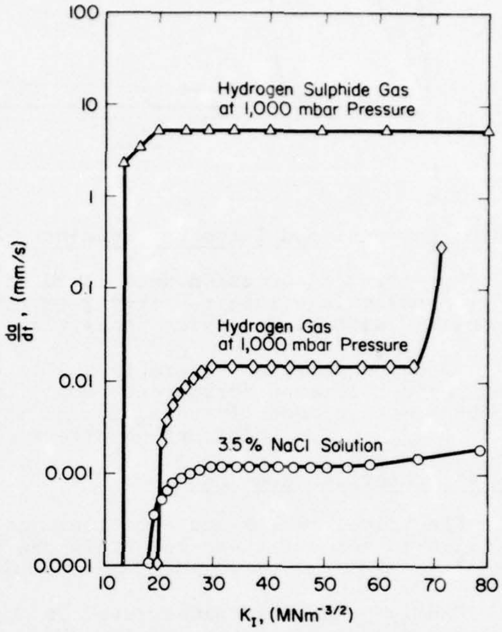


Figure 2.14. Crack velocity as a function of stress intensity for a 897 M39 at 291°K in environments of hydrogen sulfide, hydrogen, and 3.5% NaCl. From McIntyre (25).

Atmospheric corrosion is generally associated with the length of time that the RH is greater than some value above 50%; and the corrosion of lines and pumps for nominally organic fluids is proportional to the amount of water contamination.

The pervasive influence of humidity in accelerating corrosion warrants constant efforts to either remove water, lower the humidity, or counteract the effects.

2.8 Inhibitors (I)

Since the aerospace alloys are inherently reactive, especially in crevice geometries, designing for corrosion prevention requires extensive use of inhibitors. Such materials operate in the following ways:

1. Repelling water from the surfaces.

2. Blocking anodic and cathodic sites.

3. Reducing oxygen activity.

4. Precipitating insoluble layers ($CrO_4^{=} \rightarrow Cr_2O_3$). See Figure 2.7.

5. Controlling the pH in the range of insolubility of the metal's non protective oxide.

6. Lowering the potential on the surface (galvanic protection).

7. Raising the potential to give anodic protection.

8. Restricting the cathodic sites by coating.

A variety of coatings have been developed for preventing corrosion (26-33) and improvements in their formulation and application are continuing. These coatings are selected for their adhesion, flexibility, the inhibitive species they contain, and their low water permeability. These c-atings, in a simple way, are three dimensional inhibitive layers.

Chromate is widely used as a component in coatings or directly as a paint such as zinc chromate. Figure 2.15 shows the effect of chromate on the corrosion of aluminum in NaCl solutions. As suggested by Figure 2.7 the chromate performs its function by precipitating an insoluble Cr_2O_3 film.

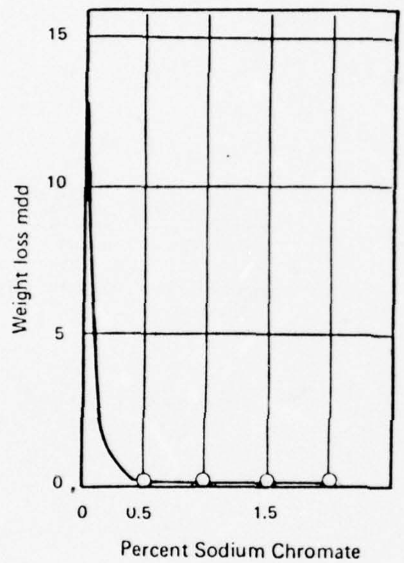


Figure 2.15. Inhibiting 7075 aluminum corrosion in 5% sodium chloride concentrations. From reference 34.

While Figure 2.6 shows that both decreasing and increasing the pH accelerates the corrosion of aluminum, Figure 2.16 shows that certain ions in addition to chromate produce significant inhibition. Disilicate is particularly effective here.

A wide range of options are available for the use of inhibitors, and the available corrosion literature together with predictions of thermodynamics provides a useful basis for improved design of corrosion prevention.

2.9 Stress (S)

Stress degrades metal according to two important corrosion processes: viz. stress corrosion cracking and corrosion fatigue. Stress is part of the environment since it is a source of mechanical potential energy just as metals in the presence of corroding environments are a source of chemical potential energy. The role of stress is very complex as a result of a variety of loading profiles which are sustained over the life of an aircraft. This variety of stresses and cyclic frequencies, to say nothing of the undercurrent of residual stresses, makes it difficult to interpret or to assign unique contributions to the chemical environment or to the stress.

These two processes, CF and SCC, are part of the same spectrum, and Figure 2.17 illustrates this relationship. CF approaches SCC either along the coordinate of R ratio, i.e. σ_{min} approaches σ_{max}, or cyclic frequency. Thus, as R approaches +1, σ_{min} approaches σ_{max}, and in the limit of R = 1, $\sigma_{min} = \sigma_{max}$ where the condition of constant load obtains. In the dimensions of cyclic frequency, increasingly long

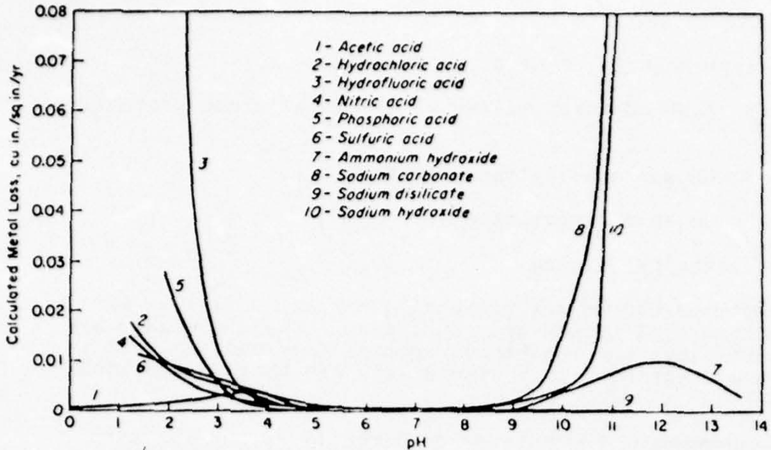


Figure 2.16. Corrosion resistance of aluminum exposed to chemicals of varying pH. From reference 35.

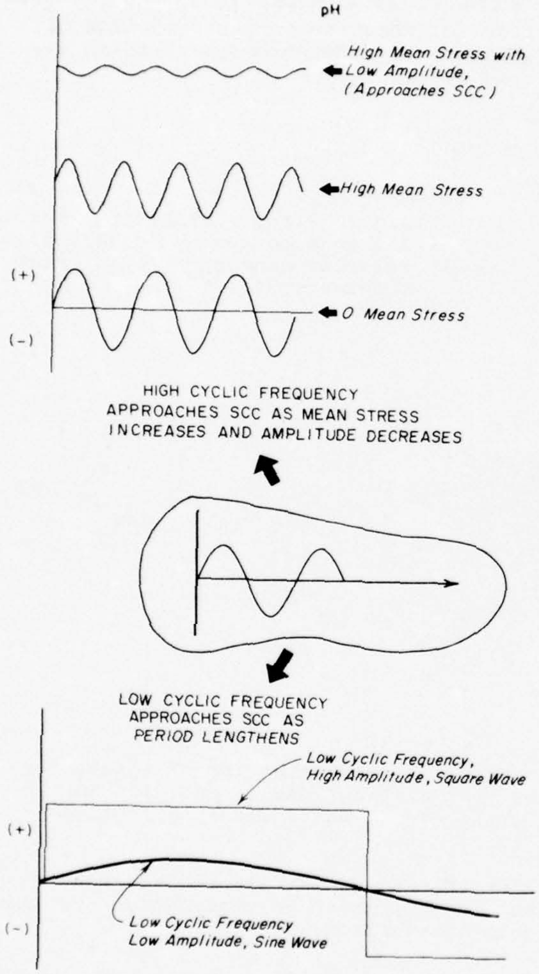


Figure 2.17. Schematic diagram showing how fatigue parameters approach constant load conditions, i.e. corrosion fatigue approaches stress corrosion cracking.

periods approach the condition of constant load when the length of the period approaches the time to failure for normal static load tests.

The mechanical properties as affected by environments, cyclic stressing, and initiation vs. propagation may be viewed simultaneously on a Speidel plot (36) as shown in Figure 2.18. Here, the horizontal lines refer to those processes which are associated with smooth surfaces of initiation processes. The sloping lines are determined for materials with pre-existing defects. This plot also defines the regions in which the various modes operate.

As the cyclic frequency is reduced, the environmental influences increase. Above some limiting cyclic frequency, usually 1-10 H_z, the environmental influence is eliminated. Figure 2.19 from Speidel shows this effect (36). A slope of -1 usually implies that each cycle is a SCC phenomenon. Lower slopes imply environmental acceleration but no associated SCC.

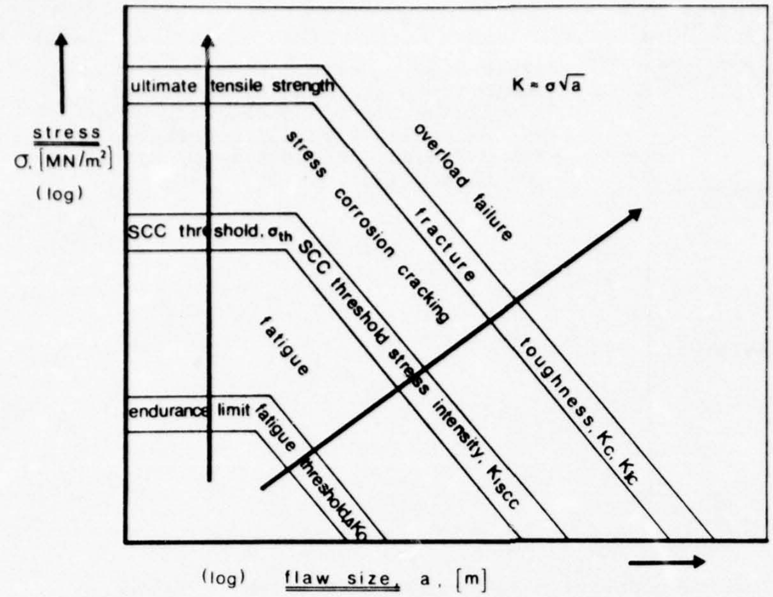


Figure 2.18. Combining smooth specimen data and fracture mechanics data: schematic illustration of materials properties which measure the resistance to fracture under monotonic loads, in aggressive environments, and under cyclic loads. From Speidel (10).

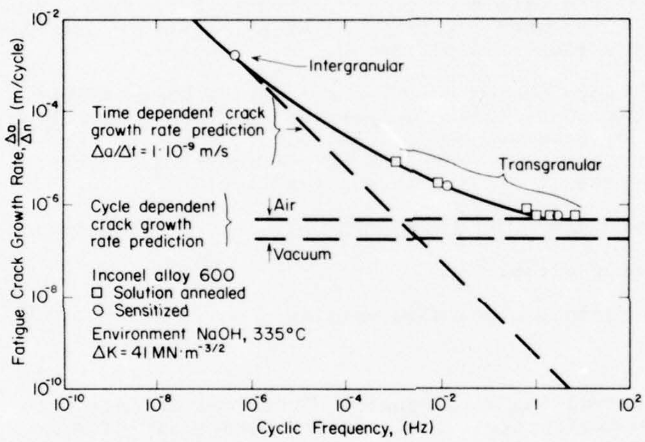


Figure 2.19. Fatigue crack growth rate for Inconel 600 in a NaOH solution at 335°C showing the transition between dependence and independence upon cyclic frequencies. The slope of -1 for $\Delta a/\Delta n$ indicates a stress corrosion cracking susceptibility at constant loads. From Speidel (36).

A final influence of the mechanical-chemical interaction is associated with wave shape of the stress cycle although wave shape is not significant in the absence of aggressive environments nor at high cyclic frequencies. However, Barsom has demonstrated (37) as have others following him that, in the presence of environments, cracks advance less rapidly as the rate of the ascending stress is increased; and the nature of the descending portion is less significant. This effect is illustrated in Figure 2.20.

2.10 Physical Nature of the Environment (P)

Corrosion processes which depend to some extent on the physical nature of the environment include erosion, cavitation, and fretting.

Erosion is an increasing problem as speeds increase, for example, with rain droplets or with solid particles in turbines.

Fretting processes depend upon slight relative motion of adjacent parts (28). Fretting per se does not cause so much damage as it does shorten the initiation process for fatigue.

In aircraft cavitation processes apply to accelerated attack in hydraulic systems, especially in landing gear assemblies. In piston engine aircraft cavitation damage occurs in the cylinders.

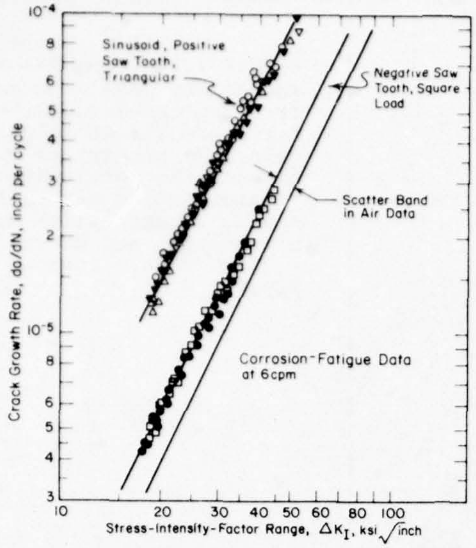


Figure 2.20. Corrosion fatigue crack growth rates in 12Ni-5Cr-3Mo steel in 3% solution of sodium chloride under various cyclic stress fluctuations with different stress-time profiles. From Barsom (37).

The other part of this physical consideration is associated with the arrangement and juxtaposition of materials. In this class of environments crevice corrosion and galvanic corrosion belong. Two major texts have been prepared on the subject of corrosion processes which are associated with crevice and galvanic corrosion processes (40, 41). Special care must be taken when materials of high reactivity are used since they tend to undergo very rapid localized corrosion.

Crevice attack, in general, is accelerated by those geometries where electrolyte is sequestered but oxygen is excluded. These geometries may result from heating metal surfaces, under deposits, under gaskets, under insulation, or under corrosion scale. When the environment in the crevice is a halide or sulfide, the attack is greatly accelerated. Designing to prevent crevice attack involves:

1. Avoiding tight unprotected geometries (i.e. crevices).

2. Reducing the size of cathodic areas.

3. Eliminating or inhibiting against aggressive species.

4. Eliminating water.

Avoiding galvanic attack means avoiding simultaneous electrical and electrochemical contact of materials where their relative cathodic kinetics are greatly different. Both large cathodic areas as well as high cathodic kinetics (even on small areas) accelerate galvanic attack.

3.0 THE NATURE OF METALS

Preventing the deterioration of metals depends upon a broad understanding of the behavior of alloys as affected by their peculiar and intrinsic properties as well as their response to outside influences. Integrating over all the properties of an alloy system produces a set of characteristics which are quite different among the important aerospace alloys. Simply looking up a single property, e.g. K_{th}, does not provide a sufficient perspective. A major advance would be achieved if designers, operators, and maintenance personnel were instructed in the implications of these sets of characteristics. To some extent, these respective sets of characteristics constitute a personality. Preventing failure over all the time regimes in which aircraft perform depends upon understanding the characteristics and implications of these metallurgical personalities.

I will not deal here with quantitative aspects of these metallurgical personalities. Further, I will note only the most prominent features. I suggest that all personnel who, in any way, are responsible for the reliable performance of aircraft should be instructed in these intrinsic alloy characteristics.

The discussion which follows describes the principal character traits which affect reliable performance for high strength steels, aluminum alloys, titanium alloys, and magnesium alloys.

3.1 High Strength Steels

3.1.1 Martensitic Transformation

The possibility of quench and tempering permits optimizing the strength and

toughness parameters of high strength steel alloys. However, this property leads also to important propensities to failure. First, as the strength is increased, both K_{I_c} and $K_{I_{scc}}$ are substantially decreased. Secondly, the maximum temperature which can be used to bake out hydrogen is limited since a too high baking temperature will reduce the strength. Thirdly, in machining, a too heavy cut will produce local heating sufficient to raise the temperature to the gamma region; and the large heat sink of the surroundings will quench this local zone to produce untempered martensite. Needless to say, this structure will serve as a site for initiating both SCC and CF.

3.1.2 Chemical Stability of Iron

The Pourbaix diagram for iron shown in Figure 2.5 shows that iron is unstable in water below pH 8 although, in the presence of oxygen, anodic protection operates. Iron possesses its greatest stability in slightly basic solutions. Also, from the H_2O/H_2 equilibrium line, one sees that iron will corrode in the absence of oxygen and that hydrogen can be liberated when iron corrodes. This behavior of iron is decidely different from aluminum and titanium.

In addition to this thermodynamic basis which proscribes the ranges of stability as affected by oxidizing conditions and the pH, iron also is subject to pitting in chloride environments in much the same way as described in Figure 2.8 for aluminum.

3.1.3 Diffusivity of Hydrogen

Hydrogen is only sparingly soluble in iron but its diffusivity is very high, being about 10^{-5} cm^2/sec compared with about 10^{-10} cm^2/sec for nickel and gamma iron alloys. This high diffusivity seems to account for the great sensitivity of iron base alloys to hydrogen embrittlement processes. This diffusivity for hydrogen in iron is uniquely high among the structural alloys.

3.1.4 Fracture Toughness of the bcc Crystal Structure

Contrary to the face centered cubic and hexaganol close packed structures, the body centered cubic structure of iron has, at low temperature, a relatively low inherent fracture toughness. While this trend is common for all high strength materials, the lower to medium strength alloys of aluminum and titanium tend to be tougher than ferritic materials at ambient conditions.

3.2 Aluminum

3.2.1 Melting Point

The low melting point of aluminum, 660°C, eliminates it from application on the leading edges of wings on high speed aircraft. It also limits the regime for preserving its metallurgical strength to essentially room temperature.

3.2.2 Precipitation Hardening

Precipitation hardening of aluminum alloys involves three important effects. First, the SCC phenomena seems to be the most virulent at the peak hardness condition. Secondly, the species used to produce significant strengthening in precipitation hardening all lead to generally destructive effects of corrosion. Copper, for example, is substantially cathodic and exacerbates pitting. Magnesium and zinc do not have stable protective films in neutral and acidic solutions as already noted in Figure 2.7. The instability of their protective films, rather than the low standard potentials, makes Al-Zn-Mg type precipitates very susceptible to accelerated corrosion.

Thirdly, the grain boundary region of the precipitation hardened material tends to be mechanically heterogeneous having large precipitates at the grain boundary adjacent to a relatively large precipitate-free zone.

3.2.3 Large Volume of Corrosion Products

The relatively large volume of corrosion products formed when aluminum corrodes leads to the phenomenon of exfoliation as well as to the possibility of high stresses which could be developed in crevice geometries. A schematic example of exfoliation is shown in Figure 3.1.

3.2.4 Chemical Reactivity

The chemical reactivity of aluminum is characterized by the Pourbaix diagram of Figure 2.6. Aluminum is characterized by its corrosion stability in neutral solutions and by its instability in both acidic and caustic solutions. Secondly, it, like the other important structural metals is susceptible to pitting in halide solutions as shown in Figure 2.8.

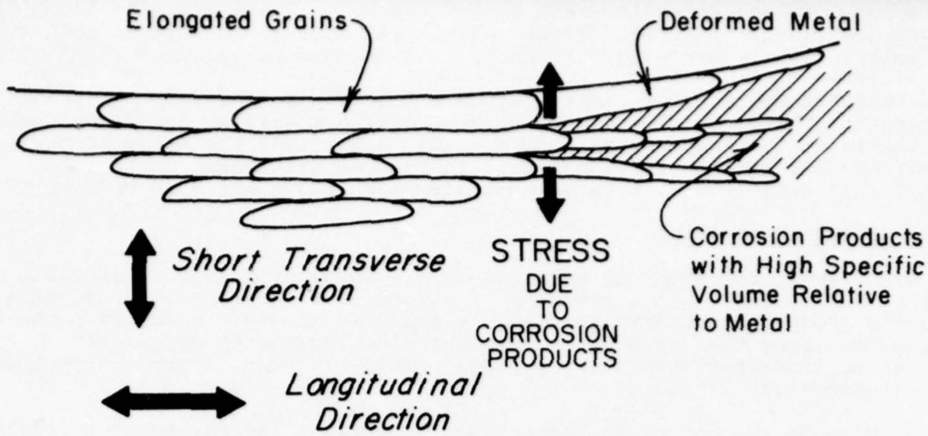


Figure 3.1. Schematic view of process of exfoliation. Here corrosion products form at grain boundaries and corrosion proceeds in longitudinal directions.

3.2.5 Anisotropy

When aluminum is deformed, its grains are deformed to produce highly anisotropic configurations. This, together with its susceptibility to corrosion attack along grain boundaries makes susceptibility to SCC and intergranular attack very directional. Thus, the SCC resistance of alloys is greatest in the longitudinal direction and lowest in the short transverse.

3.3 Titanium

3.3.1 Corrosion Resistance

Titanium exhibits excellent corrosion resistance primarily because of the broad range of stability of its protective film as shown in Figure 2.9. In oxygenated circumstances where the potential of the corroding surface is sufficiently high, the protective film is stable over the entire range of pH.

3.3.2 Hydrides

Unlike iron and aluminum, titanium readily forms hydrides. These appear to be causally related to some SCC processes. Further, their presence decreases the fracture toughness.

3.3.3 Susceptibility to SCC

While titanium possesses great general resistance to aggressive chemical environments, it is highly susceptible relative to the aluminum and steel alloys in environments based on the alcohols and nitric acids including N_2O_4. Titanium, like aluminum, is susceptible to SCC in halide environments.

3.3.4 High Solubility of Interstitial Elements

Titanium dissolves large amounts of nitrogen, oxygen, and carbon relative to aluminum and steel. This tendency leads to defective welds which may be embrittled or porous. Further, the increased hardness favors coplanar slip which increases susceptibility to transgranular SCC.

3.3.5 Anisotropy

Titanium alloys, owing to their hexagonal structure, can achieve highly anisotropic conditions depending on the fabrication process. Since the plane for transgranular SCC tends to have a constant relationship to the basal plane, this anisotropy can be manipulated to reduce the tendency for SCC.

3.4 Magnesium

3.4.1 Chemical Reactivity

The application of magnesium to aircraft is prevented or greatly modified by the

instability of the protective film at neutral and acid pH's as shown in Figure 2.7. This together with the low standard potential virtually precludes these alloys for application where any reliability is required.

4.0 THE APPROACH TO INCORPORATING CORROSION RESISTANCE INTO DESIGN

The aircraft industry is faced simultaneously with the following influences which must be maintained in a dynamic equilibrium:

1. The high priority on safety and availability.

2. The high capital cost for each aircraft as well as high operating costs.

3. Operations which impose relatively severe and unrelenting loading conditions and which involve aggressive environments.

4. The use of materials which are inherently reactive chemically or mechanically owing respectively to their low standard potentials and low threshold stress intensities for SCC, CF, and fracture.

In order to meet objectives of safety and availability, a set of preventive procedures have evolved having the following elements:

1. Requiring that resistance to chemical and mechanical degradation be built into the initial design.

2. Organizing inspection procedures which will prevent failures from occurring between inspection intervals.

3. Keeping records whose results can be dynamically fed into the design.

4. Organizing testing programs which include both large assemblies as well as specific laboratory testing where emphasis is placed on testing exactly those conditions of material and geometry which are used in manufactured equipment.

5. Placing protective action exactly where required.

These preventive procedures are discussed in the following sections.

4.1 Specification Requirements

The American aerospace weapons program has developed a military standard, MIL-STD-1568 (USAF), "Materials of Processes for Corrosion Prevention and Control in Aerospace Weapons Systems." The principal objective of this specification is to incorporate the critical features of corrosion prevention into the initial design. Important features of the specification are the following:

1. Applies during the conception, validation, development, and production.

2. Establishes a corrosion prevention advisory board.

3. Requires corrosion signoff on drawings.

4. Applies to all major contractors and subcontractors which contribute to the system.

5. Applies to all materials including lubricants, sealants, insulation, adhesives, alloys.

6. Requires that explicit corrosion control plans be submitted by contractors.

7. Requires that the contractor's corrosion team leader report directly to program management.

8. Requires that careful records of problems and resolutions be kept and be fed back into design.

9. Applies to design features which exacerbate corrosion such as drainage, crevices, residual stresses.

10. Prohibits circumstances which are known to be aggressive such as mercury (embrittles Al and Ti), graphite (good cathode), and polymers which release noxious chemicals (polyvinyl chloride).

This specification must be regarded as an enlightened approach. It places emphasis on both the dynamic processes of people interactions as well as the prohibitions and caveats which have been developed in aircraft and non-aircraft technology.

4.2 Inspection

As an evidence for the high value placed upon intermediate inspection, my other paper in this volume notes that about 25% of the cost of maintenance is spent for personnel who perform intermediate inspections. The relatively high mechanical-chemical reactivity of the aerospace alloys virtually demands a thorough and regular inspection program. Elements of such a program include certainly the following: highly trained and experienced inspection personnel; ready accessibility to critical areas; procedures for recording data which will permit precise interpretation as to local cause and mode; substantial assurance that locations which are not easily inspected are safe.

4.4 Records

The military standard described above has resulted from the dynamic feedback process made possible by keeping reasonably good records. This process is implicitly necessary for the development of progressively more reliable and economical systems.

Clearly, in addition to keeping the records, ways must be found--as well as improved--for educating designers, contractors, purchasers, operators, and maintenance personnel. A concentrated educational program is necessarily associated with keeping records.

4.5 Testing

There are two important principles in testing which apply to aircraft. First, any material which is tested and any environment selected should be exactly that which will be experienced during operation of the aircraft. This testing needs to incorporate reasonable ranges as included in the concept of "worst case."

An excellent example of inadequate prior testing was the failure of the Ti-6Al-4V alloy in the Apollo where the alloy was to contain N_2O_4. Initial qualification of the Ti-6Al-4V was performed in green N_2O_4 with a high water and low O_2 impurity--both impurities less than 1% total. The subsequent proof testing of the manufactured container was performed in red N_2O_4 where the water was lowered and the oxygen was higher--again all the impurities being less than 1%. The water concentration, in fact, was lowered in the development of the N_2O_4 production in order to make a more pure product--the idea being that "pure is good." No re-testing was performed when the change was made owing to the presumed nobility of titanium as well as the apparent innocuousness of the change. The result of this apparently small change in the N_2O_4 was very rapid transgranular SCC. The fix was simply to return to the less pure N_2O_4.

The second principle involves the testing of large components and full scale testing. This permits judging the interaction processes. Such testing prevents anyone from having to be ominscient.

4.6 Precise Location of Preventive Procedures

Much of the preventive technology in the aerospace industry depends upon the certainty that mechanical and chemical damage starts at the surface. Thus, a great deal of attention is given to corrosion resistance and stresses at the surface. This acknowledgement permits the use of heat treatments which are susceptible to SCC if the stress is in the longitudinal direction . Shot peening is valuable as a method for reducing residual stresses at the surface. The use of "wet" rivets is necessary owing to crevice corrosion in the rivet crevices together with the susceptibility to exfoliation which is inherent in high strength alloys; similar protection is not required on the longitudinal surfaces so it is not used.

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Prevention and Combat of Corrosion in Aircraft Structures

This Bibliography with abstracts has been prepared to support AGARD Lecture Series No. 84 by the Scientific and Technical Information Office of the US National Aeronautics and Space Administration, Washington, D. C., in consultation with Mr N. E. Promisel, the Lecture Series Director and Professor R. W. Staehle, Ohio State University.

It is hoped that this material will be of value to scientists and engineers and in particular to those who are new in the field.

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COSATI CODE

N74-33228*# National Aeronautics and Space Administration. Lewis Research Center, Cleveland, Ohio.
FRETTING IN AIRCRAFT TURBINE ENGINES
Robert L. Johnson and Robert C. Bill [1974] 17 p refs
Presented at the Specialists Meeting on Friction and Wear in Aircraft Systems, Munich, 11-12 Oct. 1974; sponsored by AGARD
(NASA-TM-X-71606; E-8090) Avail: NTIS HC $3.00 CSCL 21E

The problem of fretting in aircraft turbine engines is discussed. Critical fretting can occur on fan, compressor, and turbine blade mountings, as well as on splines, rolling element bearing races, and secondary sealing elements of face type seals. Structural fatigue failures have been shown to occur at fretted areas on component parts. Methods used by designers to reduce the effects of fretting are given. Author

TYPICAL CITATION AND ABSTRACT FROM *IAA*

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NAME OF MEETING

A73-37496 * # **Cyclic oxidation evaluation - Approaching application conditions.** C. A. Barrett and E. B. Evans (NASA, Lewis Research Center, Cleveland, Ohio). *American Ceramic Society, Annual Meeting and Exposition, 75th, Cincinnati, Ohio, Apr. 29-May 3, 1973, Paper.* 22 p. 6 refs.

Review of 1000 to 1200 C cyclic oxidation testing conducted on potential aircraft gas turbine Ni-, Co-, and Fe-base alloys. Furnace and burner rig testing are discussed, and the results are compared for selected alloys. The alloys fall into two groups, depending on their Cr and Al contents. One group forms mainly Cr_2O_3/chromite spinel scale(s), while the other forms alpha Al_2O_3/aluminate spinel scale(s). Spalling on thermal cycling leading to increased metal consumption is associated with the appearance of a chromite spinel. In the case of high-velocity burner rig tests this chromite forming tendency is reinforced by Cr_2O_3 vaporization depleting Cr in the alloy. In both types of tests, specific weight change is used as an indirect indicator of metal attack, since direct metal loss measurements require destructive analysis. An alternative nondestructive metal loss estimating parameter, based on a tentative mass balance gravimetric approach, shows some potential. (Author)

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HIGH TEMPERATURE CORROSION

N73-30529# Army Materials and Mechanics Research Center, Watertown, Mass. Metals Research Div.
HOT SALT STRESS CORROSION OF TITANIUM ALLOYS IN AN ADJUSTABLE DEFLECTION, MULTI-SPECIMEN BENT BEAM TEST APPARATUS
Anthony K. Wong and Milton Levy Mar. 1973 44 p refs
(Contract DAAG46-73-M-1401; DA Proj. 1T0-61102-B-32A)
(AD-763704; AMMRC-TR-73-10-7303) Avail: NTIS CSCL 11/6

An adjustable deflection, multi-specimen, bent beam test fixture was devised for conditioning sheet specimens used in the investigation of hot salt stress corrosion effects in titanium alloys. Initial tests were conducted with a Ti-5Al-2.5Sn titanium alloy at a temperature of 900F and a stress just below the yield strength. Crack developments on salt-treated surfaces were observed to increase with exposure time of 150, 500 and 1000 hours. In addition, deleterious effects of orientation and overstress were also observed. Later, efforts were made to evaluate a proprietary boron carbide coating at exposure time up to 500 hours. Preliminary results indicated the potential of the coating. (Modified author abstract) GRA

N74-14241# Solar, San Diego, Calif.
HOT CORROSION RESISTANT ALUMINIDE COATINGS OF CONTROLLED COMPOSITION FOR NICKEL BASE SUPER-ALLOYS Final Report, 15 Jan. 1971 - 9 Jul. 1973
Victor S. Moore and A. R. Stetson Jul. 1973 220 p refs
(Contract N00156-71-C-1020)
(AD-767728; RDR-1702-3) Avail: NTIS CSCL 11/3

The objective of the program was to develop and evaluate new application techniques and aluminide coatings of controlled composition for improved hot corrosion resistance of nickel-base superalloys. Three cast nickel-base alloys were included in the coating development program: Inco 713C, B1900 and TRW (or NASA) VIA. Procedures and techniques were developed for applying modified elements of known composition onto nickel-base alloys followed by aluminizing to form the beta NiAl aluminide. The modifying elements evaluated were Cr, Co, Y, La, Nd, Gd, Mischmetal, Ti, Zr, Si, Al2O3, MgO, Mo, W, Ta, and several combinations of the above refractory, reactive, and rare earth metals. A crucible sulfidation test (using 95Na2SO4-5NaCl) at 1750F was the principal screening test used during coating development. Oxidation tests at 1750F and 2000F and ballistic impact tests (followed by crucible sulfidation tests) were also used to screen the coatings. Final evaluation of selected coatings consisted of hot corrosion rig tests at 1650F and 1800F, tensile tests at room temperature, 1400F and 1800F, stress rupture testing at 1650F and 1800F and low-cycle fatigue tests at 1400F. (Modified author abstract) GRA

N74-16231# Air Force Systems Command, Wright-Patterson AFB, Ohio. Foreign Technology Div.
OXIDIZABILITY OF AN-TYPE BETA-ALLOYS OF TITANIUM AND PROTECTING THEM AGAINST GAS CORROSION
N. M. Fedorchuk, D. V. Igatov, and V. B. Gromova 9 Oct. 1973 10 p refs Transl. into ENGLISH from the publ. "Novyy Konstruktsionny Material - Titan" USSR, 1972 p 135-138
(AD-768432; FTD-HT-23-144-74) Avail: NTIS CSCL 11/6

The oxidation kinetics and phase composition of the scale of AN5, AN6, and AN6a titanium-niobium based test alloys is studied. Alloy AN5 is a composite of elements belonging to the Ti - Nb - Cr - Mo system. In the original state it has a beta-solid solution structure, which breaks down at 850C with the formation of the compound (TiNb)Cr2. The AN6 and AN6a alloys are distinguished from AN5 by aluminum and boron additions and the fact that they do not contain molybdenum. GRA

N74-18181# Battelle Columbus Labs., Ohio. Metals and Ceramics Information Center.
PROCEEDINGS OF THE 1972 TRI-SERVICE CONFERENCE ON CORROSION
Murray M. Jacobson and Anthony Gallaccio Dec. 1973 388 p refs Conf. held in Houston, Tex., 5-7 Dec. 1972
(Contract DSA900-74-C-0616)
(AD-771345; MCIC-73-19) Avail: NTIS CSCL 11/6

Contents: High temperature oxidation and sulfidation; Corrosion-induced cracking phenomena; Special topics; Aircraft and missiles; Power units; Armaments; Ships, submersibles and ocean equipment; Electronic equipment. GRA

N74-27991# United Aircraft Corp., East Hartford, Conn. Research Labs.
EFFECT OF VANADIUM AND SODIUM COMPOUNDS ON ACCELERATED OXIDATION OF NICKEL-BASE ALLOYS Final Report, 1 Mar. 1970 - 31 Dec. 1973
N. S. Bornstein, M. A. Decrescente, and H. A. Roth Apr. 1974 107 p refs
(Contract N00014-70-C-0234; NR Proj. 036-089)
(AD-778335; UARL-N911648-1) Avail: NTIS CSCL 11/6

The oxidation of nickel-base alloys in the presence of gaseous and condensed alkali sulfates, alkali vanadates and vanadium pentoxide was studied. It was found that in the presence of condensed alkali sulfates, oxide ions present in the melt react with and render the normally protective oxide scale ineffectual. The corrosion associated with alkali sulfates can be controlled by the presence of compatible oxides which preferentially react with the oxide ions to form innocuous compounds. Vanadium pentoxide, like the alkali sulfates, accelerates the oxidation rate of nickel-base supperalloys. The product of the reaction between V2O5 and the substrates is dependent upon the alloying elements present in the alloy. In the absence of alloying elements such as aluminum and titanium, the products are vanadates. However, when the alloys contain aluminum and/or titanium, the product of the reaction appears to be a glass. The study is related to corrosion inhibitions in vanadium containing fuels in gas turbines. (Modified author abstract) GRA

N74-29010# Central Inst. for Industrial Research, Oslo (Norway).
RESEARCH ON HIGH TEMPERATURE STRENGTH NICKEL BASE ALLOYS WITH SUPERIOR OXIDATION RESISTANCE Final Report, Mar. 1971 - Feb. 1973
Ingard Kvernes and Per Kofstad Dec. 1973 47 p refs
(Contract AF-AFOSR-2293-72; AF Proj. 7312)
(AD-778944; AFML-TR-73-234) Avail: NTIS CSCL 11/6

The properties of cyclic furnace oxidation and hot corrosion were studied on Ni-9Cr-6Al-(0.02-0.1)Y alloys. Samples of both as cast and wrought structures were used. Continuous weight gain measurements and detailed structural analyses were conducted. Tests in 1 atm. air up to 1000 hrs at 1000C show no spallation. At 1200C, however, spallation is occurring in addition to losses in the total weight after an initial period. A pretreatment in dry H2 (the partial pressure of O2 must be below the dissociation pressure for Cr2O3) is shown to reduce these effects. A mechanism for the process is proposed and discussed. Hot corrosion tests in combustion gases have been conducted mainly at 950C. Metallographic analyses of corroded samples show a catastrophic degradation of the samples by sulfidation and oxidation reactions. A coating of CeO2 or Al2O3 seems to be protective against combustion gases and reduces completely the internal oxidation and sulfidation attacks at 950C. Author (GRA)

N74-29999# Battelle Columbus Labs., Ohio.
OXIDATION AND HOT CORROSION OF Ni-Cr AND Co-Cr BASE ALLOYS CONTAINING RARE EARTH OXIDE DISPERSIONS Final Report, 6 Feb. 6973 - 5 Feb. 1974
Ian G. Wright, Ben A. Wilcox, and Robert I. Jaffee 11 Apr. 1974 109 p refs
(Contract N62269-73-C-0327)
(AD-779057) Avail: NTIS CSCL 11/6

The objectives of the program were to determine the effects of rare earth oxide dispersions on the oxidation and hot corrosion of Ni-Cr- and Co-Cr-base alloys, with emphasis on alumina scale-forming Co-base alloys. The results generated are intended to provide a better understanding of the compositional requirements of oxidation-resistant and hot corrosion-resistant superalloys for high-temperature service in severe environments. (Modified author abstract) GRA

N74-34951# Sherritt Gordon Mines, Ltd., Fort Saskatchewan (Alberta).
IMPROVEMENT IN THE MECHANICAL PROPERTIES AND OXIDATION RESISTANCE OF DISPERSION STRENGTHENED NICKEL-CHROMIUM ALLOYS Final Report, 1 Feb. 1972 - 30 Apr. 1973
D. H. Timbres and L. F. Norris Mar. 1974 67 p refs
(Contract F33715-72-C-1345; AF Proj. 7351)
(AD-783324; AFML-TR-74-8) Avail: NTIS CSCL 11/6

A dispersion strengthened nickel-base alloy, Ni/16Cr/5Al/2ThO2, exhibiting excellent high temperature oxidation resistance was subjected to a series of thermomechanical processing studies to optimize its mechanical properties. All properties with the exception of room temperature ductility were above the target specifications for the program. Extensive oxidation tests were conducted on an alternative composition, Ni/9Cr/6Al, with and without a dispersoid (ThO2) addition. The results indicated that the Ni/9Cr/6Al/2ThO2 alloy had generally poorer high temperature oxidation characteristics. The mechanical properties, however, were found to be similar to those of the Ni/16Cr/5Al/2ThO2 alloy. (Modified author abstract) GRA

N75-10192# Solar, San Diego, Calif.
TUNGSTEN-REINFORCED OXIDATION-RESISTANT COLUMBIUM ALLOYS Final Report, 20 Feb. 1973 - 20 Feb. 1974
Mark J. Klein and Arthur G. Metcalfe May 1974 115 p refs
(Contract N622969-69-C-0218)
(AD-783985; RDTR-1759-4) Avail: NTIS CSCL 11/4

Optimization of the columbium alloy/tungsten composites has continued for general gas turbine application in the temperature range 2000 to 2400F. Major improvements have been made in hot transverse strength, control of structural stability, Izod and ballistic impact strength, creep strength, hot corrosion at 2200F, and thermal shock resistance. These improvements have been accomplished at the expense of some loss of fail-safe life for severely damaged specimens. This composite system can be optimized for specific applications by adjustment of the matrix composition and selection of tungsten filaments with specific properties. (Modified author abstract) GRA

N75-11090# Liverpool Univ. (England). Dept. of Metallurgy and Materials Science.
HOT CORROSION OF NICKEL-BASE ALLOYS CONTAINING ALUMINUM AND MOLYBDENUM Interim Scientific Report, 15 May 1973 - 14 May 1974
John Stringer, M. E. ElDahshan, and D. P. Whittle 30 May 1974 31 p refs
(Grant AF-AFOSR-2388-72; AF Proj. 9769)
(AD-784932; EOARD-TR-75-5; ISR-2) Avail: NTIS CSCL 11/6

The effects of pre-sulfidation in H2 - 10% H2S mixtures, where the sulfur activity is sufficient to form nickel and chromium sulfides, on the oxidation behaviour of a series of Ni-Cr, Ni-Cr-Al, Ni-Cr-Mo and Ni-Cr-Al-Mo alloys was investigated. In binary Ni-15Cr alloys the presence of dispersed chromium sulfides in the alloy preclude the formation of a continuous Cr2O3 layer. The presence of molybdenum and to a lesser extent aluminum in the alloy increases the extent of attack after pre-sulfidation, particularly the depth of penetration of internal sulfides. Neither element is particularly deleterious under direct oxidation conditions, at least in flowing atmospheres. The technique of a brief pre-sulfidation treatment followed by oxidation is able to produce corrosion morphologies strikingly similar to those observed in practical hot corrosion conditions and it seems probable that the role of sulfur has been underestimated in recent mechanistic investigations. Author (GRA)

N75-15795# Little (Arthur D.), Inc., Cambridge, Mass.
INVESTIGATION OF THE POSSIBILITIES FOR ELECTROCHEMICAL CONTROL OF HOT CORROSION MECHANISMS Final Report, Dec. 1972 - Dec. 1973
Joan B. Berkowitz anp W. David Lee Apr. 1974 60 p refs
(Contract N62269-73-C-0288)
(AD-787055; ADL-75526-FR) Avail: NTIS CSCL 11/6

The effect of applied currents on the hot corrosion of nickel, pure Nichrome, Inconel 600, Hastelloy X, and a Co-Cr-Al-Y alloy in both sodium sulfate melts and a sodium sulfate seeded flame has been briefly investigated. In the molten salt bath, some evidence of anodic protection was observed with strip samples of the chromia forming alloys, Nichrome and Inconel 600. Polished spherical samples of Inconel 600 were not corroded by the molten salt until structural defects were introduced either by abrading the surface or by application of high anodic or cathodic currents. In the salt seeded flame, the rate of corrosion was affected very little by applied currents, probably because of the low current densities achievable in a flame system. Evidence was obtained for a difference in mechanism between anodically and cathodically polarized Nichrome samples, oxidation being more pronounced at the cathode and sulfidation at the anode. (Modified author abstract) GRA

N75-27152# Air Force Systems Command, Wright-Patterson AFB, Ohio. Foreign Technology Div.
OXIDATION RESISTANCE OF ALLOYS OF COMPOUND TiAl WITH NIOBIUM AT 800 DEGREES AND 1000 DEGREES C
I. A. Zelenkov 9 Dec. 1974 12 p refs Transl. into ENGLISH from Metallofizika (USSR), no. 42, 1972 p 63-66
(AD-A004445; FTD-MT-24-2689-74) Avail: NTIS CSCL 11/6

The effect of Ti or Al atom replacement by Nb on the oxidation resistance of TiAl was studied. It was found that the concentration of niobium from 5 to 10 at.% does not change the microhardness, nor the depth to which gases penetrate the alloy. F.O.S.

N75-32242# Union Carbide Corp., Parma, Ohio. Carbon Products Div.
TURBINE SHROUD ABRADABLE MATERIALS EVALUATION Final Draft Report
A. D. Butcher and J. D. Grigsby Feb. 1975 143 p
(Contract F33615-74-C-2026; AF Proj. 3066)
(AD-A010420; AFAPL-TR-75-12) Avail: NTIS CSCL 11/6

Transpiration-cooled gas turbine shroud structures were designed, built, and tested. The structures consisted of two layers of porous metal attached to an air distribution substrate. The permeability of the inner porous layer was controlled to limit and distribute the cooling air. The outer porous layer was made in a manner which permitted control of its abradability. The inner porous layer was made from a nickel-chromium alloy. Ceramic protected nickel-chromium, nickel-chromium-aluminum, and nickel-chromium-aluminum-titanium alloys were used in various samples for the outer porous layer. The samples were tested for oxidation resistance, rub tolerance, and cooling effectiveness at temperatures up to 1900F. The nickel-chromium-aluminum and nickel-chromium-aluminum-titanium alloys demonstrated properties desirable for this type of application. GRA

N76-10310# Battelle Columbus Labs., Ohio.
OXIDATION AND HOT CORROSION OF Ni-Cr- AND Co-Cr CONTAINING RARE EARTH OXIDE DISPERSIONS BASE ALLOYS Final Research Report, 13 Mar. 1974 - 12 May 1975
Ian G. Wright, Ben A. Wilcox, and Robert I. Jaffee 12 May 1975 90 p refs
(Contract N62269-74-C-0291)
(AD-A011379) Avail: NTIS CSCL 11/6

The program was undertaken to investigate the effects of alloying elements such as tungsten, tantalum and carbon on the oxidation and hot corrosion behavior of alumina-forming, dispersion-strengthened CoCrAl alloys, with the objective of developing concepts for alloys required to operate uncoated for long periods in gas turbine engines. GRA

N76-13305# Systems Research Labs., Inc., Dayton, Ohio.
INTERNAL STRUCTURE AND PHYSICAL PROPERTIES OF CERAMICS AT HIGH TEMPERATURES Final Report, 30 Jun. 1971 - 30 Nov. 1974
W. C. Tripp, J. W. Hinze, M. G. Mendiratta, R. H. Duff, and A. F. Hampton Wright-Patterson AFB, Ohio ARL Jun. 1975 277 p refs
(Contract F33615-71-C-1841; AF Proj. 7021)
(AD-A013167; SRL-6731; ARL-75-0130) Avail: NTIS CSCL 11/2

Investigations were conducted on materials behavior at high temperatures. Topics discussed include high-temperature oxidation of silicon-base materials, high-temperature corrosion of experimen-

tal Ni-Cr-Al alloys, transport properties of high-temperature oxides, mechanical properties and microstructure of high-temperature Ti-base alloys, and electron-microprobe analysis of high-temperature materials. Author

A73-37496 * # **Cyclic oxidation evaluation - Approaching application conditions.** C. A. Barrett and E. B. Evans (NASA, Lewis Research Center, Cleveland, Ohio). *American Ceramic Society, Annual Meeting and Exposition, 75th, Cincinnati, Ohio, Apr. 29-May 3, 1973, Paper.* 22 p. 6 refs.

Review of 1000 to 1200 C cyclic oxidation testing conducted on potential aircraft gas turbine Ni-, Co-, and Fe-base alloys. Furnace and burner rig testing are discussed, and the results are compared for selected alloys. The alloys fall into two groups, depending on their Cr and Al contents. One group forms mainly Cr2O3/chromite spinel scale(s), while the other forms alpha Al2O3/aluminate spinel scale(s). Spalling on thermal cycling leading to increased metal consumption is associated with the appearance of a chromite spinel. In the case of high-velocity burner rig tests this chromite forming tendency is reinforced by Cr2O3 vaporization depleting Cr in the alloy. In both types of tests, specific weight change is used as an indirect indicator of metal attack, since direct metal loss measurements require destructive analysis. An alternative nondestructive metal loss estimating parameter, based on a tentative mass balance gravimetric approach, shows some potential. (Author)

A74-23963 **Heat-resistant titanium alloys - Introduction of the UT651A alloy (Les alliages de titane résistant à chaud - Présentation de l'alliage UT651A).** L. Séraphin, R. Tricot, and R. Castro (Ugine Aciers, Ugine, Savoie, France). *Revue de Métallurgie,* vol. 71, Jan. 1974, p. 19-36. 35 refs. In French. Research supported by the Services Techniques de l'Aéronautique.

Following a review of the general metallurgical characteristics specific of heat-resistant titanium alloys, and a discussion of some of the essential requirements for their utilization in aircraft jet engines, the thermomechanical properties of a new alloy, derived from the older TA6 ZrD alloy, are presented and compared. The superior hardenability of the new alloy is shown to suggest its use in compressor disks. M.V.E.

A76-17174 **Na2SO4- and NaCl-induced hot corrosion of six nickel-base superalloys.** Y. Bourhis and C. Saint John (Paris, Ecole Nationale Supérieure des Mines, Corbeil-Essonnes, Essonne, France). *Oxidation of Metals,* vol. 9, Dec. 1975, p. 507-528. 16 refs. Research supported by the Délégation Générale à la Recherche Scientifique et Technique.

The short-time hot-corrosion behavior of six industrial nickel-base superalloys was investigated with static deposits of Na2SO4 or NaCl or both in still air. The oxidation kinetics and scale morphologies were measured with traditional laboratory techniques - thermobalance, metallography, electron microprobe, and X-ray analyses. Susceptibility to hot corrosion was found to be correlated to the type of scale produced during simple oxidation. Alloys forming an Al2O3 scale were found to be susceptible to Na2SO4 deposits, independent of their chromium content. The quantity of Na2SO4 deposit dictated the nature of the attack and, under certain conditions, the refractory element alloy additions appeared to play an essential role. Alloys containing Cr2O3 or TiO2 in the simple oxidation scale proved to be sensitive to NaCl attack. Again, the severity of the attack within the susceptible alloy group was not related to the chromium or titanium content. Although less intensive than the Na2SO4-induced hot corrosion, NaCl contaminations provoked extensive spalling. All of the hot-corrosion types encountered in this study were interpreted in the light of existing theories. (Author)

N75-76542 Air Force Systems Command, Wright-Patterson AFB, Ohio.
STRESS RUPTURE STRENGTH OF TITANIUM ALLOYS UNDER CONDITIONS OF THEIR CONTACT WITH SODIUM CHLORIDE
N. G. Plekhanova Oct. 1973 9 p Transl. into ENGLISH from Mono. Novyi Konstrukt. Material, Titan, 1972 p 183-186
(AD-770935; FTD-HT-23-155-74)

In this work the effect of salt corrosion on the stress-rupture strength of Titanium alloys is determined, metallographic studies of the nature of fracture are carried out, and some forms of surface protection are evaluated (cold hardening, nickel plating). Studies were carried out at 400, 350, and 300C. Alloy VT22 (4.5% Al) was studied in rods and OT4 - in sheets of three melts (3.65-2.5% Al). Author

N75-76610 Liverpool Univ. (England). Dept. of Metallurgy and Materials Science.
HOT CORROSION OF GAS TURBINES Interim Scientific Report, 15 May 1972 - 14 May 1973
John Stringer, M. E. El-Dahshan, and D. P. Whittle Jul. 1973 13 p
(Contract AF-AFOSR-2388-72)
(AD-767792; EOARD-TR-73-22)

Discrepancies between early hot-corrosion models based on sulphidation and more recently reported data obtained by a molten salt fluxing technique are discussed. The hot corrosion role of sulphur in the absence of salt was tested by presulphidizing specimens at high and low sulphur partial pressures and then oxidizing them. Results show that certain features of the practical hot corrosion reaction are not well-modeled by the salt-fluxing model and that sulphur played a more important part than predicted. Author

N76-72089 Battelle Columbus Labs., Ohio. Metals and Ceramics Information Center.
PROCEEDINGS OF GAS TURBINE MATERIALS IN THE MARINE ENVIRONMENT (1974)
John W. Fairbanks and Irving Machlin Jun. 1975 588 p Conf. held at Marine Maritime Academy, Castine, Maine, 24-26 Jul. 1974 Sponsored in part by Naval Ship Engineering Center, Hyattsville, Md. and Naval Air Systems Command, Wash. D. C.
(Contract DSA900-75-C-1803)
(AD-A013436; MCIC-75-27)

The purpose of the 1974 conference was to continue naval air and surface fleet coordination in the area of hot-corrosion research and materials developments to mitigate the problem. Specifically, the objectives are to make department of defense personnel, contractors and interested individuals aware of the intended use of gas turbine engines at sea, the mechanism of the engine life-limiting problem hot corrosion, the materials development to combat the problem and testing conducted to verify the materials selection. Topics covered include: service experience in the marine environment; mechanism of hot corrosion; developments in materials and coatings; test and evaluation of materials and coatings.

76-01001 Cincinnati Univ., Ohio. Dept. of Materials Science and Metallurgical Engineering.
BASIC MECHANISMS PROVIDING OXIDATION RESISTANCE IN STRUCTURAL METALS AT HIGH TEMPERATURES Final Report, 20 Feb. - 20 Dec. 1972
Rosa J. Casimir Feb. 1973 47 p
(Contract N00019-72-C-0186)
(AD-758097; NASA-0186-3)

The purpose of the study was research of a fundamental nature in order to further our knowledge about high-temperature oxidation behavior of structural, titanium-base alloys operating above 900C. Oxidation characteristics of Ti-4.32 wt.% Cb and Ti-4.37 wt.% Ta alloys are reported for th3 temperature range 1000-1200C. The influence of oxygen pressure of 10, 100, and 760 torr on the oxidation kinetics of Ti-4.37 wt.% Ta, as well as sintering effeczs in the oxide are also investigated. The oxidation behavior of Ti-4.32 wt.% Cb in dry, oxygen and air at 1000 and 1100C is reported. Author

76-01002 S.E.R.F., Inc., Pensacola, Fla.
SUMMARY OF 500 HOUR CO2 SCALE INHIBITOR TEST IN A 10gph RECYCLING FLASH EVAPORATOR
Dec. 1973 27 p
(Contract N00600-73-C-0471)
(AD-781993)

The report summarizes the results of a fifty hour test to determine the feasibility of using CO2 gas to prevent scale formation in a high temperature desalination recycling flash evaporator. The tests show conclusive results that CO2 can

prevent scale formation on Titanium surfaces at temperatures above 220F and increase heat transfer rates 25% above conventional Cu-Ni surfaces. The tests also conclude that the CO_2 requirement is well within the CO_2 recovery rate experienced aboard submarines. Modified Author Abstract

76-01003 Naval Ship Engineering Center, Hyattsville, Md.
PROCEEDINGS OF GAS TURBINE MATERIALS, 1972
Charles L. Miller Oct. 1972 178 p Conf. held at Naval Ship Engineering Center, Hyattsville, Md., Oct. 1972 See also AD-A013436, Jun. 1975
(AD-A016684)

This conference was organized to provide a forum for technically responsible representatives of government and industry to discuss the many facets of sulfidation corrosion and methods of reducing its effects. The major problem encountered in operating gas turbines in the marine environment is sulfidation, which limits engine life and restricts performance improvements. Sulfidation is also a significant problem with naval aircraft jet engines. Programs of common interest to surface ships and aircraft include accelerated salt ingestion testing, non-destructive test techniques, and reprocessing of air-cooled blades and vanes. Materials and coatings which ameliorated engine resistance to the sulfidizing environment were discussed. Testing techniques to determine sulfidation resistance and engine life were presented.

76-01004 Air Force Systems Command, Wright-Patterson AFB, Ohio Aerospace Research Labs.
DEGRADATION OF Ni-8Cr-6Al AT 1000 C IN GASEOUS ENVIRONMENTS CONTAINING CARBON OR SULFUR
H. C. Graham, A. F. Hampton, and H. H. Davis, Jr. 1974 22 p Pub. in Proc. of the Intern. Symp. on Metal-Slag-Gas Reactions and Process., Toronto (Ontario), May 1975 p 763-783
(AF Proj. 7021)
(AD-A017821, ARL-75-0240)

As part of a large program to characterize the hot-corrosion behavior of Ni-8Cr-6Al, this alloy was exposed to CO/0.45 v/o CO_2 and H_2/5.18 v/o H_2S gas mixtures at 1000 C and 150 torr total pressure. The behavior in these mixtures is compared with the results for normal oxidation (O_2) and Na_2SO_4-coated oxidation. In H_2/H_2S the degradation of the alloy material is shown to be extensive, with various sulfides--including liquid nickel sulfide--being formed. Likewise, the alloy integrity is attacked in CO/CO_2 by the rapid formation of grain-boundary and intragranular chromium carbide. The effects of such alloy alteration on subsequent oxidation resistance and/or mechanical integrity are discussed. Author

02

EROSION AND CAVITATION

N73-23651# Pratt and Whitney Aircraft, West Palm Beach, Fla. Research and Development Center.
EROSION RESISTANT COATING FOR TITANIUM Final Report, 30 Jun. 1971 - 30 Jul. 1972
William J. McAnally, III Jan. 1973 88 p refs
(Contract DAAG46-71-C-0173; DA Proj. 1T0-62105-A-328)
(AD-758276; PWA-FR-5243; AMMRC-CTR-73-6) Avail: NTIS CSCL 11/3

The objective of the program was to develop the application of TIKOTE-C on the Ti-6Al-4V alloy with minimum degradation of mechanical properties. The approach for accomplishing this objective was to protect the titanium microstructure with an intermediate nickel barrier, as well as to provide a ductile layer which might inhibit crack propagation. In addition, embrittling effects due to gas absorption during the coating process were minimized by using a lower process temperature. The program was divided into two major categories: (1) TIKOTE-C coating application development, and (2) extensive mechanical tests. A brief evaluation of the fatigue characteristics and erosion resistance of nickel-plated and titanium diboride-coated titanium test specimens was made. (Author Modified Abstract) GRA

N74-16263# Michigan Univ., Ann Arbor. Dept. of Engineering Mechanics.
ANALYSIS OF RAIN EROSION OF COATED MATERIALS Technical Report, Jun. 1972 - Jun. 1973
George S. Springer, Chen-I. Yang, and Poul S. Larsen Sep. 1973 72 p refs
(Contract F33615-72-C-1563, AF Proj. 7340)
(AD-769448; AFML-TR-73-227) Avail: NTIS CSCL 11/3

The behavior of coat-substrate systems subjected to repeated impingements of liquid droplets was investigated. The system studied consisted of a thick homogeneous substrate covered by a single layer of homogeneous coating of arbitrary thickness. Based on the uniaxial stress wave model, the variations of the stresses with time were determined both in the coating and in the substrate. Employing the fatigue theorems established for the rain erosion of homogeneous materials, algebraic equations were derived which describe the incubation period, and the mass loss of the coating past the incubation period, in terms of the properties of the droplet, the coating and the substrate. The results were compared to available experimental data and good agreement was found between the present analytical results and the data. The differences between the uniaxial stress wave and the uniaxial strain wave models were also evaluated by calculating according to both models (a) the stress at the coat-liquid interface, (b) the stress that would occur in the substrate in the absence of the coating, and (c) the stress in the coating after the first wave reflection from the substrate. Author (GRA)

A75-31858 # **Damage of aircraft gear-pump casing by pitting erosion (Uszkodzenia korpusow lotniczych pomp zebatych przez erozje kawitacyjna).** J. Kowalski. *Technika Lotnicza i Astronautyczna*, vol. 29, Apr. 1975, p. 16-18. 8 refs. In Polish.

The purely mechanical, purely chemical, and mechanico-chemical aspects of a corrosion theory for gear pumps of aircraft hydraulic systems are examined. It is shown that the mechanism of pitting erosion is quite complex and that it depends to a great degree on such factors as the physicochemical state of the working fluid, contamination by mechanical impurities, and the temperature. Means of eliminating pitting are examined. V.P.

A75-33938 * # **The dynamics of atmospheric dust particles in aircraft auxiliary power radial inflow turbines.** W. B. Clevenger, Jr. and W. Tabakoff (Cincinnati, University, Cincinnati, Ohio). *American Institute of Aeronautics and Astronautics, Fluid and Plasma Dynamics Conference, 8th, Hartford, Conn., June 16-18, 1975, Paper 75-844*. 12 p. 9 refs. NASA-supported research.

The results of analytical and experimental studies of the trajectories that atmospheric dust particles follow as they move through a radial inflow turbine are presented. The study reveals the nature of the impacts that occur within the turbine and indicates which surfaces are expected to experience the most severe erosion. In addition, a dimensionless parameter is derived which can be used during preliminary design analysis to indicate the sizes of the particles that will be most damaging to the turbine. (Author)

A75-46883 # **Study of cavitation erosion in aggressive media (Issledovanie kavitatsionnoi erozii v agressivnykh sredakh).** L. D. Gavrilova, L. P. Kravtsova, A. E. Potapenko, and E. S. Chistiakov. *Samoletostroenie. Tekhnika Vozdushnogo Flota*, no. 37, 1975, p. 40-43. In Russian.

Experimental results on the resistance of several materials to cavitation in magnetostriction devices at 20 kHz are reported. Experiments were conducted with nitric, sulfuric, and hydrochloric acid, hydrogen peroxide, and kerosene. Cavitation and corrosion losses are compared. It was shown that materials with low corrosion resistance are especially liable to cavitation destruction. P.T.H.

76-02001 Catholic Univ. of America, Washington, D.C. Inst. of Ocean Science and Engineering.
CAVITATION EROSION-CORROSION MODELING
Terence McGuinness and A. Thiruvengadam 1974 21 p Pub. in Am. Soc. for Testing and Materials, 1974 p 30-45 Rept. no. ASTM-STP-567
(Contract N00014-67-A-0377-0008; NR Proj. 062-436)
(AD-A010697; ASTM-STP-567)

Due to the increased occurrence of cavitation erosion in hydrodynamic systems operating in an ocean environment, there is a need to study the role of corrosion on the process of cavitation erosion. Previously, for noncorrosive systems, correlation of experimental data with the theory of erosion resulted in a time-scale modeling law of erosion. The changes in this scaling law due to corrosion were then investigated. A high-frequency, 20 kHz, piezoelectric vibratory apparatus was employed to generate erosion time history data for HY-130, Hy-80, SAE 1020 steels, and Al 6086 H117 at several different erosion intensities in sea and distilled water. Results indicated that the relative erosion rate curves for materials susceptible to corrosion were different, and that the changes due to corrosivity increased with increasing erosion intensities. By coupling changes in corrositivity with maximum erosion rate increases, and times to the maximum rates, it is possible to make prototype performance predictions for either seawater or distilled water conditions. Qualitative relationships were found between the relative erosion rates and galvanic potentials of tested materials. A mechanism was proposed to account for the corrosive influence on erosion based on hydrogen-generated micropit destruction of a material surface that accelerates cavitation erosion. Author

03

MANUFACTURING PROCESSES

N75-30155# United Aircraft Corp., Stratford, Conn. Sikorsky Aircraft Div.
FABRICATED HELICOPTER TRANSMISSION HOUSING ANALYSIS Final Report, 18 Dec. 1972 - 18 Oct. 1973
Alexander Korzun and Stephen Schuman Jan. 1975 298 p
(Contract DAAJ02-73-C-0022; DA Proj. 1F1-62203-A-119)
(AD-A008995; USAAMRDL-TR-74-14) Avail: NTIS CSCL 21/5

The helicopter transmission housing study provides a transmission housing design superior to the conventional magnesium cast housing. The new design is a welded steel fabricated truss-like structure, corrosion resistant, and not susceptible to creep. The aircraft selected for this study was the U.S. Army CH-54B helicopter. The new fabricated truss-like housing was designed to be interchangeable with the present CH-54B magnesium main transmission housing. It meets all the interface and functional requirements of the cast housing design. Loads for flight and crash conditions, as well as stiffness criteria, were developed to permit structural analysis and comparison with the existing casting design. GRA

N76-17236# Frankford Arsenal, Philadelphia, Pa.
THERMOMECHANICAL PROCESSING OF ALUMINUM ALLOY INGOTS
J. Waldman, H. Sulinski, and H. Markus Aug. 1975 37 p refs *Presented at the 21st Sagamore Army Mater. Res. Conf., Sagamore, N. Y., 13-16 Aug. 1974*
(DA Proj. 1T1-62105-AH-85)
(AD-A014980; FA-TA-75052) Avail: NTIS CSCL 11/6

The Materials Engineering Division at Frankford Arsenal is involved in an extensive research effort aimed at upgrading the engineering properties of wrought high strength 7000 series aluminum alloys through thermomechanical processing of the ingot material. The development of two new ingot thermomechanical processing techniques, ISML-ITMT and FA-ITMT, is presented. The effects of these techniques on the recrystallization behavior, grain morphology, tensile properties, fracture toughness and stress corrosion resistance of high purity 7075 alloy sheet and plate is presented. The recrystallization of 7075 alloy into a fine grained material was found to be controlled by the distribution of the major alloying elements, Zn, Mg and Cu, as well as by that of the ancillary element, Cr. The results showed that for a given standard temper, i.e., T6, T76 and T73, high purity ITMT processed 7075 alloy has finer grain size, equivalent strength and better ductility, fracture toughness and stress corrosion characteristics than commercial 7075 alloy. The work also showed that high purity ITMT processed 7075 alloy in the FTMT temper (a temper involving a deformation stage between an initial and a final artificial aging stage) has higher strength, ductility and fracture toughness than commercial 7075-T6 alloy.
Author (GRA)

A74-23962 **Recent developments and utilization criteria of titanium alloys in the aircraft industry (Développements récents et critères d'emploi des alliages de titane pour l'industrie aéronautique).** R. Molinier, L. Séraphin, R. Tricot, and R. Castro (Ugine Aciers, Ugine, Savoie, France). *Revue de Métallurgie,* vol. 71, Jan. 1974, p. 1-17. 40 refs. In French.

Recently accomplished titanium technology advances conducive to expanding application opportunities and improved titanium-alloy performance in aircraft engines and airframes are examined in light of the basic criteria governing the utilization of titanium in these two important application areas. Prospects of further progress are reviewed, along with future titanium-alloy utilization trends. M.V.E.

A74-23967 **Utilization of titanium and its alloys in the manufacture of helicopters and airplane frames (Utilisation du titane et de ses alliages dans la fabrication des hélicoptères et des cellules d'avions).** A. Bourgeois and G. Sertour (Société Nationale Industrielle Aérospatiale, Suresne, Hauts-de-Seine, France). *Revue de Métallurgie,* vol. 71, Jan. 1974, p. 87-98. In French.

A75-44560 **Advances in engine manufacturing production techniques.** R. Scharwächter. *Interavia,* vol. 30, Apr. 1975, p. 358, 360.

Major production techniques in joining, machining, and surface treatment of aircraft engines are described, and general guidelines are given for their use in the production of individual components. Current welding procedures, cutting methods, electrochemical and electroerosion milling processes, and flame and plasma coating techniques are outlined. C.K.D.

N75-78389 Air Force Systems Command, Wright-Patterson AFB, Ohio. Foreign Tech. Div.
THE WELDING AND BRAZING OF THIN WALLED PIPES
A. M. Kitaev and A. Gubin Oct. 1973 142 p Transl. into ENGLISH from Mono. Svarka i Paika Tonkostennykh Truboprovodov, N. P., 1972 p 1-133
(FTD Proj. 60108; FTD Proj. T72-01-40)
(AD-768806; FTD-MT-24-719-73)

Contents: General information on pipes; methods and technology of pipes welding; methods and technology of pipe brazing; pipes of aluminum alloys with steel connecting parts; surface treatment of pipes; strength of welded and brazed pipe joints; and increasing pipe strength.

04

NON-DESTRUCTIVE TESTING AND INSPECTION

N74-17282# Grumman Aerospace Corp., Bethpage, N.Y. Research Dept.
DEVELOPMENT OF A NUCLEAR MICROPROBE TECHNIQUE FOR HYDROGEN ANALYSIS IN SELECTED MATERIALS Final Report, 18 Apr. 1972 - 18 Jul. 1973
Gerald M. Padawer and Philip N. Adler Oct. 1973 95 p refs
(Contract N00019-72-C-0404)
(AD-770856; RE-464) Avail: NTIS CSCL 11/6

The Lithium Nuclear Microprobe (LNM) has been developed to the point where it now is a unique and reliable nondestructive tool for the measurements of hydrogen concentration depth profiles in material surfaces. The hydrogen concentration calibration was performed using hydrogen-in-titanium NSB standards and Kapton, a polyimide film. Hydrogen surface concentrations were measured in cadmium and chromium plated D6AC steel samples, smooth and fractured Ti-6Al-4V surfaces that had been exposed to a stress corrosion environment, and smooth surfaces of 7075 aluminum alloys that had been exposed to conditions of stress corrosion. Hydrogen concentration depth profiles were measured in cadmium plated D6AC steel and 7075 aluminum alloy samples. Very high hydrogen concentrations found in these samples were linked to mechanical property degradation and corrosion. Thus the LNM has emerged as a proven, currently unmatched, diagnostic technique for accurate in situ measurements of localized hydrogen concentrations. (Modified author abstract) GRA

N75-14752# Radio Corp. of America, Burlington, Mass. Aerospace Systems Div.
INVESTIGATION OF INSPECTION AIDS Final Report, 18 Apr. 1973 - 24 May 1974
Richard L. Calhoon, Fred W. Hohn, James A. McNamee, Bruce B. Wierenga, and T. N. Cook Jul. 1974 199 p refs
(Contract DAAJ02-73-C-0059; DA Proj. 1F1-62205-A-11903)
(AD-787333; USAAMRDL-TR-74-44) Avail: NTIS CSCL 15/5

The investigation of inspection aids was performed to identify specific inspection requirements and recommend relatively small aids or indicators, current or conceptual, that will enhance the troubleshooting inspection/preventive maintenance process for Army helicopters. Inspection requirements and procedures for six helicopter types (AH-1, UH-1, CH-47, CH-54, OH-6, OH-58) were analyzed. Significant inspections were identified and the effectiveness and adequacy of presently used procedures and techniques was assessed. Areas where the inspector is highly dependent upon subjective judgment or cumbersome or ineffective procedures are employed were determined. Surveys of available off-the-shelf vendor aids and candidate conceptual inspection aids which offer improved inspection efficiency in these areas were performed. (Modified author abstract) GRA

N75-29483# Royal Aircraft Establishment, Farnborough (England). Structures Dept.
A SHORT STUDY OF THE EFFECT OF A PENETRANT OIL ON THE FATIGUE LIFE OF A RIVETED JOINT
P. H. ONeill and R. J. Smith London Aeron. Res. Council 1975 12 p Supersedes RAE-TR-73174; ARC-35284
(ARC-CP-1305; RAE-TR-73174; ARC-35284) Avail: NTIS HC $3.25; HMSO 32P; PHI $1.45

Laboratory fatigue tests on riveted joints, half of which had been impregnated with a water-displacing, oil-based penetrant which is commonly being used in airline service to combat corrosion are described. The results showed that the lives of the treated specimens were significantly shorter than those of the untreated specimens. Further work, however, would be necessary to determine the effect of the penetrant under more realistic conditions over a longer time. Author (ESRO)

A73-36825 # **Estimation of corrosion damage levels in thin-walled structural elements by the punching method (Otsenka stepeni korrozionnogo porazheniia tonkostennykh elementov konstruktsii metodom prodavlivaniia).** A. M. Vorobeikov and V. A. Gorodetskii (Kievskii Institut Inzhenerov Grazhdanskoi Aviatsii, Kiev, Ukrainian SSR). *Fiziko-Khimicheskaia Mekhanika Materialov*, vol. 9, no. 2, 1973, p. 96-98. In Russian.

Description of an apparatus designed for the evaluation of the extent of corrosion damage in thin-walled structural elements by measuring the force required for piercing an element wall area with a punch. A corrosion damage measurement technique using this apparatus is proposed as a more practical substitute for techniques involving destruction of specimens. V.Z.

A75-38629 **Possibilities concerning a use of borescope inspection methods in nondestructive material testing and the significance of these methods (Möglichkeiten der Borescope-Untersuchungsmethoden in der zerstörungsfreien Werkstoffprüfung und deren Aussagekraft).** H.-G. Straatmann (Lufttransport-Unternehmen GmbH, Dusseldorf, West Germany). *(Deutsche Gesellschaft für Zerstörungsfreie Prüfverfahren, Vortragstagung über Zerstörungsfreie Materialprüfung, Berlin, West Germany, May 5-7, 1975.) Materialprüfung*, vol. 17, July 1975, p. 220, 221. In German.

Industrial glass-fiber borescopes are used for the examination of cavities in the case of accessibility difficulties. The employment of the borescope technique in the case of an inspection involving an aircraft engine is discussed. The engine consists of five different modules. Openings for borescope inspection are provided in each module. G.R.

76-04001 Edgewood Arsenal, Aberdeen Proving Ground, Md.
USING EDDY CURRENTS TO DETECT INTERNAL CORROSION IN CHEMICAL MUNITIONS Technical Report, Jan. 1972 - Dec. 1973
Ronald L. Frailer Aug. 1974 23 p
(DA Proj. 5721247)
(AD-786522; EP-TR-74039)

A number of chemical munitions are housed in thin-walled aluminum containers which could be subjected to corrosion from the chemical agent they contain. This project resulted in the development of an eddy-current inspection method to detect internal corrosion in thin-walled chemical munitions. The method can be used for judging shelf life of munitions suspected to contain progressive corrosion and for eliminating potential leakers.

05

FAILURE ANALYSIS

N73-30969# National Materials Advisory Board, Washington, D.C.
APPLICATION OF FRACTURE PREVENTION PRINCIPLES TO AIRCRAFT Final Report
Feb. 1973 274 p refs
(Contract DA-49-083-OSA-3131)
(AD-764513; NMAB-302) Avail: NTIS CSCL 01/3

The elements of current fracture control plans and associated technologies were reviewed. After reviewing the status, applicability, and potential of the elements and technologies, it was concluded that fracture control plans and development of related technologies not only afford an opportunity to reduce catastrophic failures of aircraft structures and structural maintenance but also can help to quantify many structural material, design, nondestructive evaluation, and maintenance decisions that now are made on a relatively qualitative basis. The Committee recommended careful trade studies, together with caution and flexibility, in the use of existing criteria and prior to the issuance of new criteria. (Modified author abstract) GRA

N76-17226# Advisory Group for Aerospace Research and Development, Paris (France).
MANUAL ON FATIGUE OF STRUCTURES. VOLUME 2: CAUSES AND PREVENTION OF STRUCTURAL DAMAGE. CHAPTER 6: FRETTING; CORROSION DAMAGE IN ALUMINIUM ALLOYS
William G. Barrois Nov. 1975 89 p refs
(AGARD-MAN-9-Vol-2) Avail: NTIS HC $5.00

The question of damage due to fatigue, fretting, corrosion, and stress corrosion is discussed in detail. The causes of failure are outlined, along with the characteristics of electrochemical corrosion. Prevention of and protection against stress corrosion and electrochemical corrosion were investigated.

A75-12726 **Failure analyses of aircraft accidents. II.** J. B. Shah (Ministry of Transport, Engineering Laboratory, Ottawa, Canada). *Metals Engineering Quarterly*, vol. 14, Nov. 1974, p. 23-29.

Failures in aircraft components caused by decarburization, corrosion, abnormal misalignment, and overloading are discussed. Precautionary methods used to reduce these failures are included. To illustrate the effects of fretting and corrosion failure two designs, one attributed to insufficient design and the other to inadequate maintenance, are considered. Certain stress-bearing components are covered such as connecting rods, spar tubes, spring legs, eyebolts, and drive shafts. T.S.

76-05001 Naval Air Engineering Center, Lakehurst, N.J.
INVESTIGATION OF INTERNAL CORROSION AND EVALUATION OF NON-SKID COATINGS ON MARK 7 JET BLAST DEFLECTORS Final Report
George A. Gehring, Jr. Dec. 1975 79 p
(AD-A020127; NAEC-ENG-7875)

The Mark 7 jet blast deflector (JBD) is a 36 foot by 14 foot aluminum barrier erected at a 50 degree angle to the flight deck, for the purpose of protecting waiting aircraft and handling personnel from the jet blast of a plane being launched. In order to cool the panels enough to allow safe passage of personnel and machinery and to prevent actual physical damage to the JBD by the heat of the jet engines, sea water is pumped through the internal passages of the panels. Ships personnel, in the past, have reported that internal corrosion was a continuing maintenance problem, requiring frequent and costly rework. NAVAIRENGCEN undertook a program to assess the severity of corrosion damage occuring on the JBD's and to investigate potential methods for controlling internal corrosion. NAVAIRENGCEN also initiated a study to further evaluate the relative ability of metallic non-skid coatings to perform in the JBD carrier deck environment. Color illustrations are reproduced in black and white.

06

FRACTURE, FATIGUE, AND STRESS CORROSION CRACKING

N73-24591# Aerospace Corp., El Segundo, Calif.
STRESS CORROSION CRACKING AND HYDROGEN EMBRITTLEMENT OF HIGH-STRENGTH FASTENERS Final Report, Jun. 1971 - Jan. 1972
James K. Stanley 30 Apr. 1973 53 p refs
(Contract F04701-72-C-0073)
(AD-758754; TR-0073(3413-1)-1; SAMSO-TR-73-131) Avail: NTIS CSCL 11/6

Unexpected, brittle failures of high-strength fasteners on aerospace vehicles have been caused by stress corrosion cracking (SCC) and by hydrogen stress cracking (HSC). Despite extensive study, much remains to be learned about the phenomena. The poorly understood failure mechanisms are difficult to differentiate, especially in the field. There is a growing use of the term SCC to describe failure by both mechanisms. Data are given to characterize the classes. For low alloy carbon steels heat-treated to yield strengths below approximately 160 ksi, stress corrosion is not a problem, nor is hydrogen embrittlement (delayed cracking) very common. Above 160 ksi, difficulties can occur. The high-strength, precipitation-hardening, stainless steels have varying degrees of resistance to stress-corrosion cracking and hydrogen embrittlement, depending upon strength level and heat-treating procedures that influence the microstructure. (Author Modified Abstract) GRA

N73-25618# Aerospace Research Labs., Wright-Patterson AFB, Ohio.
EFFECT OF THERMOMECHANICAL TREATMENT ON THE STRESS CORROSION CRACKING BEHAVIOR OF BETA 3 TITANIUM
Dale O. Condit and John H. Seats Feb. 1973 17 p refs
(AF Proj. 7021)
(AD-759166; ARL-73-0017) Avail: NTIS CSCL 11/6

The effect of thermomechanical treatment on the stress corrosion cracking susceptibility of Beta III (Ti-11.5Mo-6Zr-4.5Sn) alloy was investigated. Specimens of the alloy were cold worked 0, 2, 5, 10, 20, and 50% and precipitation hardened prior to fabrication into tensile test specimens. Five specimens of each thermomechanical treatment condition were tensile tested in order to obtain yield strengths. The remaining specimens were exposed to an alternate wet/dry environment of 3.5 w/o NaCl solution at ambient temperature under a load of 80% of yield. (Author Modified Abstract) GRA

N73-27467# Martin Marietta Corp., Baltimore, Md.
THE INFLUENCE OF A HEAT TREATMENT ON THE STRESS CORROSION SUSCEPTIBILITY OF A TERNARY Al-5.3 PERCENT Zn-2.5 PERCENT Mg ALLOY Technical Report No. 7
A. J. Sedriks, J. A. Green, and D. L. Novak May 1973 14 p refs Submitted for publication
(Contract N00014-67-C-0496; NR Proj. 031-716)
(AD-761207; MMR-TR-73-07C; TR-7) Avail: NTIS CSCL 11/6

The influence of heat treatment on the stress-corrosion susceptibility of a ternary Al-5.3% Zn-2.5% Mg alloy has been examined in terms of four variables. These variables are the cooling rate from the solution treatment temperature, holding time at room temperature, aging time at a temperature below the G.P. zone solvus and aging time at a temperature above the G.P. zone solvus. Variables which markedly influence the stress-corrosion susceptibility of the Al-Zn-Mg alloys were found to be the cooling rate after solution treatment and the aging time at temperature above the G.P. zone solvus. These results are discussed in terms of variations in the grain boundary microstructure. Author (GRA)

N73-27469# Martin Marietta Corp., Denver, Colo.
EFFECT OF VACUUM ENVIRONMENT ON MECHANICAL BEHAVIOR Annual Report, Jan. 1971 - Jan. 1973
Irvin R. Kramer Feb. 1973 36 p refs
(Contract F44620-69-C-0065; AF Proj. 9768)
(AD-760529; MCR-73-16; AFOSR-73-0685TR) Avail: NTIS CSCL 11/6

The surface layer stress of titanium alloy (6Al/4V and 5Al/2.5Sn) was measured in methanol-chloride solutions as a function of voltage. The surface layer stress was found to increase markedly as the specimen became more anodic. It is proposed that stress-corrosion cracking is associated with the formation of a surface layer of critical strength to support a pileup of dislocations to cause fracture. The stress corrosion behavior of titanium and aluminum (2014-T6) was determined on specimens with and without the surface layer. A marked increase in the stress corrosion cracking resistance was achieved by eliminating the surface layer. Author (GRA)

N73-29538# Catholic Univ. of America, Washington, D.C. Inst. of Ocean Science and Engineering.
FURTHER INVESTIGATIONS ON THE RELATIONSHIP BETWEEN INTERNAL DAMPING AND SUSCEPTIBILITY TO STRESS CORROSION CRACKING
Michael Ryan and A. Thiruvengadam Jun. 1973 22 p refs
(Contract N00014-67-A-037-0003)
(AD-762777) Avail: NTIS CSCL 11/6

The experimental procedure developed by Hochrein and Thiruvengadam and further modified as reported in the report is an elegant tool for determining susceptibility to stress corrosion cracking. Susceptibility can be detected long before any microscopic evidence of cracking becomes noticeable. This procedure is adaptable to different shapes and thicknesses of materials, and further development would lead to a compact, portable nondestructive test instrument to be used in testing aircraft wings, ocean structures, etc., in the field. GRA

N73-30525# Rensselaer Polytechnic Inst., Troy, N.Y. Materials Div.
THE EFFECT OF MEAN STRESS AND ENVIRONMENT ON CORROSION FATIGUE BEHAVIOR OF 7075-T6 ALUMINUM
L. V. Corsetti and D. J. Duquette 10 Apr. 1973 31 p refs
(Contract N00014-67-A-0117-0012; NR Proj. 036-093)
(AD-763455; TR-2) Avail: NTIS CSCL 11/6

Axial fatigue tests were performed on a 7075-T6 aluminum alloy in tension-compression and under superimposed positive mean stresses in dry air and in aqueous 0.5N NaCl solution. Both corrosive environments and positive mean stresses resulted in lower fatigue lives but no interaction between these variables was observed. Crack initiation in air occurred at electropolish pits at inclusion/alloy interfaces and propagated primarily in a Stage I (crystallographic) mode. A model for environment assisted cracking is presented which suggests that hydrogen induced cleavage is responsible for the degradation in fatigue properties of this alloy. (Modified author abstract) GRA

N73-32383# Boeing Commercial Airplane Co., Seattle, Wash.
APPLICATION OF RELIABILITY ANALYSIS TO AIRCRAFT STRUCTURES SUBJECT TO FATIGUE CRACK GROWTH AND PERIODIC STRUCTURAL INSPECTION Final Report, 16 Jul. 1972 - 31 Mar. 1973
I. C. Whittaker and S. C. Saunders Wright-Patterson AFB, Ohio AFML Jun. 1973 47 p refs
(Contract F33615-71-C-1134; AF Proj. 7351)
(AD-764775; AFML-TR-73-92) Avail: NTIS CSCL 01/3

A method of simulating crack growth has been investigated. The proposed model, which is based on linear elastic fracture mechanics theory, allows for the variability in crack growth behavior found in the experimental data of various materials. Given a reference stress intensity factor range and central tendency values for the crack growth rate and the exponent of the stress intensity factor excursions of a material in a specified configuration, Monte Carlo simulation is used to select various combinations of parameters. These are then used to generate fatigue cracks, on the assumption that crack growth rate is a power function of the stress intensity factor range. The residual strength of the cracked structure is considered to be a decreasing function of the induced crack length. The probability of crack detection also depends on the generated crack and is assumed to improve with increasing crack length. However, this improved detection probability is modified by the probability that the crack location is not the one being inspected. (Modified author abstract) GRA

N73-32433# Naval Research Lab., Washington, D.C.
FATIGUE-CRACK GROWTH OF Ti-6Al-2Cb-1Ta-0.8Mo ALLOY IN AIR AND NATURAL SEA WATER ENVIRONMENTS
W. R. Cares and T. W. Crooker Jul. 1973 15 p refs
(AD-765318; NRL-MR-2617) Avail: NTIS CSCL 11/6

Studies of low-cycle fatigue-crack propagation in air and natural sea water environments were conducted on a Ti-6Al-2Cb-1Ta-0.8Mo alloy. The effects of cathodic polarization of the alloy in sea water were evaluated. The alloy was tested as single-edge-notched, side-grooved samples in zero-to-tension loading and the results were analyzed in terms of crack-tip stress-intensity parameters. The alloy showed no evidence of fatigue sensitivity to either natural sea water or to applied cathodic potential. These results are in agreement with other studies on a similar Ti-6Al-2Cb-1Ta-0.8Mo alloy and a Ti-6Al-4V alloy of similar yield strength and fracture toughness, but are in sharp contrast to the high degree of environmental sensitivity previously exhibited by a Ti-7Al-2Cb-1Ta alloy. Author (GRA)

N74-11350# Army Materials and Mechanics Research Center, Watertown, Mass. Metals Research Div.
EFFECT OF TENSILE DEFORMATION AND HEAT TREATMENT ON THE STRESS CORROSION SUSCEPTIBILITY OF AN Al-Zn-Mg ALLOY
C. Shastry and Milton Levy Jul. 1973 28 p refs
(DA Proj. 1T0-62105-A-328)
(AD-766683; AMMRC-TR-73-34) Avail: NTIS CSCL 11/6

The effect of a series of thermomechanical treatments on the stress corrosion susceptibility of an Al-6.86 w/o Zn-2.35 w/o Mg alloy in a 3.5 percent sodium chloride solution was studied by bent beam type stress corrosion tests. The results indicated that for specimens without a room temperature preaging treatment, a 2 percent plastic deformation before the final aging at 150C increased the stress corrosion resistance. No such improvement resulted from a 5 percent deformation. The difference in the stress corrosion susceptibility for the two treatments was attributed to the difference in the dislocation and precipitate distributions in the matrix in the two cases. For both the undeformed specimens and specimens deformed by 2 percent, preaging at room temperature resulted in lower values of stress corrosion time to failure. This reduction in stress corrosion resistance was attributed to incomplete elimination, during aging, of grain boundary solute segregation in the preaged specimens. Author (GRA)

N74-11354# Aluminum Co. of America, New Kensington, Pa. Alcoa Research Labs.
COMPARISON OF ALUMINUM ALLOY 7050, 7049, MA52, AND 7175-T736 DIE FORGINGS Final Technical Report, 1 Jun. 1971 - 31 Dec. 1972
James T. Staley Wright-Patterson AFB, Ohio AFML May 1973 130 p refs
(Contract F33615-69-C-1644; AF Proj. 7351)
(AD-766328; AFML-TR-73-34) Avail: NTIS CSCL 11/6

Die forgings in aluminum alloys 7050, 7049, and MA52 were fabricated and evaluated for resistance to stress-corrosion cracking, quench sensitivity, and fracture toughness. In addition, all Alcoa data on 7050, 7049, and special process 7175-T7X die forgings were examined and the properties were collated. Stress-corrosion resistances were evaluated using the severest combinations of forging type and test conditions. All of these newer alloys were less quench sensitive than alloy 7075, and all developed better combinations of resistance to stress-corrosion cracking and fracture toughness than 7075-T6 and 7079-T6 at equal strengths. Because it developed the best combination of properties, alloy 7050 is a preferred selection for use as die forgings of relatively heavy section thickness for the aerospace industry. This alloy also can be supplied as hand forgings, plate, extrusions, and sheet. Special process 7175 is an equally good selection for die forgings of thin to moderate section thickness. Author (GRA)

N74-11361# Rensselaer Polytechnic Inst., Troy, N.Y. Materials Div.
STRESS CORROSION CRACKING SUSCEPTIBILITY AND AGING CHARACTERISTICS OF Al-Zn-Mg-Ti ALLOYS
C. Chen and G. Judd Aug. 1973 23 p refs
(Contract N00014-67-A-0117-0009)
(AD-766838; TR-5) Avail: NTIS CSCL 11/6

A comparison of the stress corrosion cracking (SCC) susceptibility of four aluminum-zinc-magnesium alloys was determined as a function of processing and composition variables, particularly aging treatment and titanium additions. The SCC tests were performed employing a four point loaded constant moment apparatus in a 3.5% sodium chloride solution at room temperature. The alloys were studied as part of a microstructure and microcomposition characterization program in order to determine the effect of these variables on the SCC susceptibility and mechanical properties of the Al-Zn-Mg system. (Modified author abstract) GRA

N74-11362# Aluminum Co. of America, New Kensington, Pa. Alcoa Research Labs.
MECHANICAL PROPERTIES, FRACTURE TOUGHNESS, FATIGUE, ENVIRONMENTAL FATIGUE CRACK GROWTH RATES AND CORROSION CHARACTERISTICS OF HIGH-TOUGHNESS ALUMINUM ALLOY FORGINGS, SHEET AND PLATE Final Report, May 1971 - Feb. 1973
C. F. Babilon, R. H. Wygonik, G. E. Nordmark, and B. W. Lifka Apr. 1973 248 p refs
(Contract F33615-71-C-1571, AF Proj. 7381)
(AD-766335; AFML-TR-73-83) Avail: NTIS CSCL 11/6

The mechanical properties, including toughness and fatigue, fatigue crack growth rates and corrosion characteristics have been determined for a total of 56 lots of 7049-T73 and 7175-T736 forgings, 7475-T61 and T761 sheet, and 2124-T851 plate. Supplemental data for bare and Alclad 7475 sheet and 2124-T851 plate are also presented. Tables of computed design mechanical properties and typical stress-strain and compressive tangent modulus curves were prepared. The rates of fatigue crack propagation of these products generally do not vary significantly with specimen orientation. Humid and salt fog environments increased the rate of fatigue crack propagation for most specimens. Propagation is slower in 2124-T851 plate than for 2024-T851 plate but rates for sheet alloys 7475-T61, 7475-T761 and Alclad 7475-T61 are essentially equivalent as are rates for 7175-T736 and 7075-T7352 hand forgings. The 7175-T736 forgings, 7475-T761 sheet and 2124-T851 plate have a high resistance to exfoliation while the 7049-T73 forging and the 7475-T61 sheet show some susceptibility to exfoliation. All of the materials are resistant to stress corrosion exfoliation. All of the materials are resistant to stress corrosion cracking when stressed in the longitudinal and long-transverse grain direction. The resistance to SCC in the short-transverse direction of all the materials is representative of the respective alloys and tempers. Author (GRA)

N74-13263# Boeing Commercial Airplane Co., Seattle, Wash.
EVALUATION OF AFC 77 MARTENSITIC STAINLESS STEEL FOR AIRFRAME STRUCTURAL APPLICATIONS Final Technical Report, 1 Jun. 1971 - 31 May 1973
R. G. Caton and C. S. Carter Sep. 1973 75 p refs
(Contract F33615-71-C-1550; AF Proj. 7351)
(AD-767597; D6-60225; AFML-TR-73-182) Avail: NTIS CSCL 11/6

The fabrication and properties of two high-strength stainless martensitic steel forgings are described. A high level of fracture toughness was achieved in the AFC 77 forging at a tensile strength level of 235 ksi. Stress corrosion resistance, however, was similar to that of competitive steels. The fracture toughness, stress corrosion, and fatigue properties developed in the AFC 77B forging at a tensile strength of 260 ksi were similar to those of currently used steels. Cracking problems were experienced with both forgings during heat treatment. The stress corrosion resistance of AFC 77 was no higher than that of competitive steels. The target tensile strength of 275 ksi was not achieved in the AFC 77B landing gear forging. A lower tensile strength would appear to be more appropriate for this alloy in heavy section form. The fracture toughness, stress corrosion, and notch fatigue properties were very similar to those of medium alloy steels. Although both AFC 77 and AFC 77B are stainless types of steel, it is considered that the low stress corrosion resistance would necessitate plating and painting to prevent the ingress of moisture. (Modified author abstract) GRA

N74-16236# Aerospace Research Labs., Wright-Patterson AFB, Ohio
CORROSION STUDIES OF Fe-Ni AND BETA-3 TITANIUM ALLOYS Final Report, 1 Jun. 1968 - 19 Jun. 1972
Dale O. Condit Oct. 1973 12 p refs
(AF Proj. 7021)
(AD-769480; ARL-73-0136) Avail: NTIS CSCL 11/6

This investigation was conducted to elucidate factors involved in the stress corrosion cracking of alloys of interest to the aerospace industry. The study was concentrated in two particular areas: (1) Potentiodynamic and potentiostatic polarization studies of high purity Fe-Ni alloys in chloride-containing and non-chloride-containing H2SO4; and (2) Time-to-cracking for notched and unnotched Beta III titanium alloys which had been given a variety of thermomechanical treatments. GRA

N74-16240# Naval Ship Research and Development Center, Annapolis, Md.
FATIGUE CRACK PROPAGATION IN A 5456-H117 ALUMINUM ALLOY IN AIR AND SEA WATER
H. P. Chu Oct. 1973 29 p refs
(SF54541011)
(AD-769467; NSRDC-4169) Avail: NTIS CSCL 11/6

Fatigue data on a 5456-H117 aluminum alloy have been obtained in air and sea water by fracture mechanics methods. It is found that the presence of sea water increases the crack growth rates and lowers the threshold stress intensity. The data for five stress ratios are correlated with two empirical equations. The effect of sea water on fatigue cracking is also examined by electron fractographs. Author (GRA)

N74-18185# Naval Research Lab., Washington, D.C.
STUDY OF A TITANIUM WIRE ROPE DEVELOPED FOR MARINE APPLICATIONS Final Report
Darrell A. Milburn 2 Nov. 1973 24 p refs
(RR0230345)
(AD-771355; NRL-7625) Avail: NTIS CSCL 11/6

The mechanical properties and fatigue performance of a titanium wire rope have been experimentally determined. The rope has a nominal diameter of 1/4-in. and is of 7 x 7 structural form. Other salient constructional details of the rope include the use of two titanium alloys and two wire lubricants. Furthermore, lay lengths of the rope and of individual strands were increased over those for similarly constructed steel ropes. The overall test program consisted of two major parts: static tensile tests and acial fatigue tests. For purposes of comparison, stainless-steel and galvanized-steel wire ropes of the same nominal diameter and 7 x 7 form were also subjected to these tests. Test results indicate that the strength-to-weight ratio and stretch characteristics of the titanium rope are superior to those of the steel ropes. However, the fatigue-life data suggest that it would fail as a part of a marine structure in a significantly shorter period of time than would either of the two less expensive steel ropes. (Modified author abstract) GRA

N74-20140# Ohio State Univ Research Foundation, Columbus.
STRESS CORROSION CRACKING OF TITANIUM AND TITANIUM BASE ALLOYS IN AQUEOUS AND GASEOUS MEDIA Final Report, 1 Mar. 1972 - 30 Jun. 1973
F. H. Beck and M. G. Fontana Sep. 1973 84 p refs
(Contract F33615-72-C-1917; AF Proj. 7312)
(AD-773245; AFML-TR-73-268) Avail: NTIS CSCL 11/6

Oxygen was found to increase significantly the stress corrosion cracking susceptibility of titanium alloys to methanol and bromine environments and the initial exposure stage is highly sensitive to the presence of moisture which can absorb on the surface and provide a protective film of water. Cracking planes in single crystal specimens were affected by stress level, chemical factors, and specimen orientation. Depth profiles of hydrogen concentration by ion microanalyses were made of cathodically charged commercially pure titanium and titanium alloys and stress was found to be a factor in determining the tendency for absorption of hydrogen. The importance of anodic dissolution in the stress corrosion cracking process is considered and discussed in depth. (Modified author abstract) GRA

N74-21148# Naval Research Lab., Washington, D.C.
STRESS CORROSION CRACKING PROPERTIES OF TWO ALUMINUM-MAGNESIUM ALLOYS
F. D. Bogar and C. I. Fujii Jan. 1974 14 p refs
(NRL Proj. M01-30; ZF54544002)
(AD-774496; NRL-MR-2724) Avail: NTIS CSCL 11/6

The SCC behavior of two Alcoa Al-Mg alloys -- a commercial alloy, 5456-H117, and an experimental alloy, N-H117, is described. These materials were studied in the as-received and aged conditions for susceptibility to cracking in 3.5% NaCl solution. Double cantilever beam specimens were machined from the one-inch thick plates of the two alloys in the SL, TL, and LT orientations. All of the specimens were fatigue pre-cracked to facilitate initiation of a pop-in crack when bolt loaded to start the SCC tests. After three days immersion in the corrodent, the specimens were mechanically broken apart and the fracture surface examined for visual evidence of SCC. The as-received specimens were insensitive to SCC in these tests with the exception of one N-H117 specimen. All of the aged specimens of both alloys were susceptible to SCC. Author (GRA)

N74-21151# Lockheed Missiles and Space Co., Palo Alto, Calif. Research Lab.
DEVELOPMENT OF ENGINEERING DATA ON THICK-SECTION ELECTRON BEAM WELDED TITANIUM Final Report, Mar. 1971 - Jun. 1973
John G. Bjeletich Aug. 1973 199 p refs
(Contract F33615-71-C-1338; AF Proj. 7381)
(AD-774051; LMSC-D352462; AFML-TR-73-197) Avail: NTIS CSCL 11/6

The report provides a vital portion of the basic engineering data necessary for the design of reliable and efficient airframe structures involving electron-beam weldments in titanium alloys. Tensile, fracture toughness, and subcritical crack growth properties of both base metal and weldments have been obtained for 1- and 2-in. Ti-6Al-4V and 1-in. Beta III plate. Test temperatures ranged from -65F to 175F and the test environments included laboratory air, water, salt water and JP-4 jet fuel. The concept of stress intensity factors from linear elastic fracture mechanics is used to quantitatively assess the load carrying capacity and crack growth resistance of the test materials. Fracture toughness and tensile properties are tabulated while the fatigue crack propagation and stress corrosion cracking rates are presented in a graphic format. GRA

N74-22219# Army Materials and Mechanics Research Center, Watertown, Mass.
STRESS CORROSION CRACKING OF URANIUM ALLOYS Final Report
Walter F. Czyrklis and Milton Levy Dec. 1973 18 p refs
(DA Proj. 1T1-62105-A-349)
(AD-774256; AMMRC-TR-73-54) Avail: NTIS CSCL 11/6

The study was carried out to determine the critical threshold intensity for stress corrosion cracking of several uranium alloys which are candidates for ballistic penetrator and nuclear shell applications. The data reported here are for alloys in the as-extruded condition only and will serve as base-line data for future studies involving the solution-treated-and-aged alloys. GRA

N74-23108# Advisory Group for Aerospace Research and Development, Paris (France).
METALLURGICAL ASPECTS OF FATIGUE AND FRACTURE
(AGARD-R-610) Avail: NTIS HC $7.75

The proceedings of a conference to investigate the fatigue and fracture behavior of aerospace structural alloys are presented. The effect of heat treatment to prevent stress corrosion was analyzed to determine possible changes in the mechanical properties of the materials. The subjects discussed include the following: (1) metallurgical aspects of fatigue and fracture toughness, (2) developments in fatigue and fracture, (3) thermomechanical procedures to improve the properties of high strength aluminum, magnesium, zinc, copper alloys, and (4) the influence of microstructure on the growth of fatigue cracks.

N74-26040# Naval Ship Research and Development Center, Annapolis, Md.
THE EFFECT OF FILLER METAL CHEMISTRY AND HEAT TREATMENT ON THE WELDABILITY OF THE Ti-6 Al-2.5 Mo ALLOY
Joseph L. Cavallaro Feb. 1974 69 p refs
(SF54541)
(AD-775599; NSRDC-4189; NSRDC-28-631) Avail: NTIS CSCL 11/6

Determination was made of the effects of combined variations in weld-metal chemistry and postweld heat treatment on the mechanical properties and sea-water stress-corrosion-cracking properties of Ti-6Al-2.5Mo weldments. The composition range studied included 4% to 7% aluminum and 0.5% to 2.5% molybdenum. Good fracture toughness and stress-corrosion-cracking resistance for weld metal in the Ti-Al-Mo-O alloy system are achieved at the 110,000 pounds per square inch yield strength level. No degradation of properties was produced in the

heat-affected zone of Ti-6Al-2.5Mo weldments. The results of this investigation indicate that a tougher and more ductile Ti-100 alloy weldment could be developed through control of microstructure in the Ti-Al-Mo-O and Ti-Al-V-O alloy systems. (Modified author abstract) GRA

N74-27026# Dayton Univ. Research Inst., Ohio.
ENGINEERING DESIGN DATA FOR ALUMINUM ALLOY 2124-T851 THICK PLATE Technical Report, Aug. 1972 - Sep. 1973
Kim A. Fudge and Raymond E. Jones Jan. 1974 33 p refs
(Contract F33615-72-C-1282; AF Proj. 7381)
(AD-777177; UDRI-TR-73-63; AFML-TR-73-310) Avail: NTIS CSCL 11/6

Tensile, fracture, fatigue, fatigue crack growth, and stress corrosion properties for aluminum alloy 2124-T851 thick plate were determined. Material property comparisons were then drawn between the 2124-T851 alloy and its parent alloy, 2024, in the T851 condition. A comparison of the mechanical properties of aluminum alloy 2124-T851 and 2024-T851 revealed that the 2124-T851 alloy exhibited similar tensile properties with possibly less short transverse ductility, superior fracture toughness, comparable fatigue properties with slightly lower smooth fatigue resistance, and identical fatigue crack growth rates. The 2124-T851 alloy also demonstrated good stress corrosion resistance. (Modified author abstract) GRA

N74-29009# Martin Marietta Aerospace, Denver, Colo.
EFFECT OF VACUUM ENVIRONMENT ON MECHANICAL BEHAVIOR Final Report, Jan. 1973 - Jan. 1974
Irvin R. Kramer Feb. 1974 54 p refs
(Contract F44620-69-C-0065; AF Proj. 9782)
(AD-778484; MCR-74-51; AFOSR-74-0589TR) Avail: NTIS CSCL 11/6

The time to failure and the crack propagation velocity of titanium (6Al-4V) and a 4130 steel were measured as a function of applied potential and concentration of the solutions. A mechanism for stress-corrosion cracking is proposed based on the formation of a strong surface layer. It is also suggested that the films, formed as a result of interaction between the metal and the SCC medium, strongly influence the strength of the surface layer. Author (GRA)

N74-29996# Army Materials and Mechanics Research Center, Watertown, Mass.
STRESS CORROSION CRACKING SUSCEPTIBILITY OF BETA TITANIUM ALLOY 38-6-44: CANDIDATE ALLOY FOR SCOUT TORSION BAR Final Report
Walter F. Czyrklis and Milton Levy Apr. 1974 12 p refs
(DA Proj. 1T0-62105-A-328)
(AD-779414; AMMRC-TR-74-10) Avail: NTIS CSCL 11/6

The threshold stress itensities for stress corrosion crack propagation in beta titanium alloy 38-6-44, Ti-3Al-8V-6Cr-4Mo-4Zr, has been determined in salt water and methanolic solutions. The alloy was immune to stress corrosion cracking in aqueous sodium chloride solutions (marine environment). However, in methanolic solutions, the alloy was very susceptible to SCC. This marked susceptibility in methanolic solutions can be mitigated by the addition of sodium nitrate as an inhibitor. Crack extension in the alloy was transgranular and failure occurred by brittle quasicleavage in methanolic solutions. Author (GRA)

N75-11968# Naval Air Development Center, Warminster, Pa. Air Vehicle Technology Dept.
CLEANING AND CORROSION CONTROL OF AVIONICS EQUIPMENT AT ALL LEVELS OF MAINTENANCE Progress Report
W. E. MacKenzie and W. E. Knight 30 Apr. 1974 21 p
(AD-784975; NADC-74049-30) Avail: NTIS CSCL 01/3

This report covers a survey of cleaning and corrosion problems encountered with avionics systems, the application of a new cleaner for components, and a process for corrosion control of avionics components and systems at the three maintenance levels. Author (GRA)

N75-12136# Naval Research Lab., Washington, D.C.
ACOUSTIC EMISSIONS AND STRESS-CORROSION CRACKING IN HIGH-STRENGTH ALLOYS Final Report
T. R. Tucker and C. T. Fujii Aug. 1974 15 p refs
(NRL Proj. 63M01-30; ZF54544002)
(AD-785009; NRL-MR-2879) Avail: NTIS CSCL 11/6

The usefulness of acoustic emission data (i.e., stress wave emission - SWE) to studies of stress-corrosion cracking (SCC) of high-strength alloys was explored. Single-edge-notched, precracked cantilever specimens were used to study the stress-corrosion-crack growth and SWE characteristics of a high-strength stainless steel and a titanium alloy. SWE data correlate reasonably well to crack growth measurements by conventional beam deflection techniques for high-strength stainless steel but is too insensitive for reliable detection of crack extension in the titanium alloy. The use of SWE data to define the energetics of discrete cracking events are currently beyond the capabilities of existing equipment and analytics. Author (GRA)

N75-12142# Martin Marietta Labs., Baltimore, Md.
OBSERVATIONS ON THE STRESS CORROSION CRACKING OF AN Al-5 PERCENT Zn-2.5 PERCENT Mg TERNARY AND VARIOUS QUARTERNARY ALLOYS
J. A. S. Green and W. G. Montague Aug. 1974 29 p refs
(Contract N00014-74-C-0277; NR Proj. 031-716)
(AD-785020; MML-TR-74-23C) Avail: NTIS CSCL 11/6

Studies were undertaken to test a concept of controlling stress-corrosion crack propagation in Al-Zn-Mg alloys through the use of minor alloying additions of elements known to retard hydrogen ion recombination such as Cd, As, Zr and Cr. Results indicated that the concept was invalid since the minor alloying additions themselves exerted a more profound influence on the grain boundary microstructure. Specifically, the microstructural features of grain boundary particle size and interparticle spacing were found to correlate with stress corrosion susceptibility. Auger electron spectroscope studies also revealed a correlation between the concentration of Zn and Mg within the precipitate-free zone and the susceptibility to cracking. (Modified author abstract) GRA

N75-12374# Lehigh Univ., Bethlehem, Pa. Inst. of Fracture and Solid Mechanics.
LOAD AND ENVIRONMENT INTERACTIONS IN FATIGUE CRACK GROWTH
T. T. Shih and R. P. Wei May 1974 28 p refs Presented at the Conf. on the Prospects of Advan. Fracture Mech., Delft, Netherlands, 24-28 Jun. 1974
(Contract N00014-67-A-0370-0008; NR Proj. 036-097)
(AD-785249; IFSM-74-61; TR-2) Avail: NTIS CSCL 11/6

The influences of environment on delay and on fatigue crack growth under programmed loading were examined for a mill annealed Ti-6Al-4V alloy. Test environments included dehumidified argon, air (with 30-60% relative humidity), distilled water, and 3.5% NaCl solution. The effects of load sequence and block size on fatigue under programmed loads were investigated also. Experimental results show that the mildly aggressive environments (atmospheric moisture and distilled water) have little effect on delay. Salt solution, on the other hand, has a significant effect on delay and on crack growth under programmed loading; the effect on delay being dependent on frequency or hold-time. Both load sequence and block size can significantly alter fatigue life under programmed loading. The need for further fundamental understanding of load and environment interactions in fatigue is discussed. (Modified author abstract) GRA

N75-13971# Rensselaer Polytechnic Inst., Troy, N.Y. Materials Div.
MICROSTRUCTURAL CHARACTERIZATION AND STRESS CORROSION CRACKING SUSCEPTIBILITY OF Al-Zn-Mg-Ti ALLOYS
C. Chen and Gary Judd Sep. 1974 20 p refs
(Contract N00014-67-A-0117-0009)
(AD-785907; TR-6) Avail: NTIS CSCL 11/6

The effects of adding small amounts of titanium to age-hardening Al-Zn-Mg alloys have been studied by transmission electron microscopy, mechanical atests, and stress corrosion cracking (SCC) tests. The zinc, magnesium, and titanium content of the alloys was varied and the effect of aging upon these alloys was examined. Multiple stages of aging were observed for several of the titanium addition alloys. The resistance to SCC of the Al-Zn-Mg ternary in an aqueous solution (3.5%NaCl) at room temperature was significantly improved in the titanium addition alloy with 0.12% as compared to an alloy with 0.23% Ti reported upon previously. The addition of 0.09%Ti to Al-7%Zn-2%Mg alloy produces a finer grain boundary precipitation and no deleterious effect on the SCC property. Author (GRA)

N75-15796# Aluminum Co. of America, Alcoa Center, Pa. Physical Metallurgy Div.
TEST AND EXPLORATORY DEVELOPMENT OF AN OPTIMUM ALUMINUM ALLOYS SYSTEM FOR SHIP STRUCTURES Final Technical Report, 23 Jun. 1972 - 23 Jul. 1974
Ralph W. Rogers, Jr., William D. Vernam, and M. Byron Shumaker 23 Jul. 1974 78 p refs
(Contract N00024-72-C-5571; SF5410011)
(AD-787568; Rept-56-AC223) Avail: NTIS CSCL 11/6

Evaluation of plate fabricated in the laboratory from a series of Al-Mg alloys having magnesium contents of 7.0 to 9.5% showed an alloy designated as CS19 met the contract requirement of an as-welded yield strength of 30 ksi minimum. Fracture toughness and resistance to general corrosion, to exfoliation and to initiation of stress-corrosion cracks were at least equivalent to present 5456-H116 or H117 alloys. MIG weldments of CS19 plate produced with CS19 electrode and by a practice which provides interpass cooling to 250F were highly resistant to stress-corrosion cracking even after thermal treatment at 212F to simulate metallurgical changes taking place during long periods of service. Nominal composition of CS19 is Al-8.25 Mg-0.4 Mn-0.1 Cr with 0.12 max. Fe and 0.10 max. Si. (Modified author abstract) GRA

N75-17501# Rensselaer Polytechnic Inst., Troy, N.Y. Materials Div.
MICROSTRUCTURAL EFFECTS IN THE FATIGUE BEHAVIOR OF METALS AND ALLOYS
Norman S. Stoloff and David J. Duquette 30 Aug. 1974 204 p refs
(Contract N00014-67-A-0117-0010; N00014-67-A-0117-0012; NR Proj. 031-745; NR Proj. 036-093)
(AD-A001096) Avail: NTIS CSCL 11/6

This review examines the various stages of fatigue damage on the basis of changes in slip character and dislocation sub-structures resulting from solid solution alloying, thermomechanical treatments or precipitation hardening. Cyclic hardening and softening are related to fatigue life of a wide variety of alloy systems, including pure metals, commercial alloys, intermetallic compounds and directionally solidified eutectics. The influence on fatigue behavior of variations in structure produced by processing (e.g., casting defects, inclusions, surface notches) also are considered. Finally, the effects of temperature and aggressive environments on crack nucleation and propagation are related to metallurgical structure. GRA

N75-19435# Carnegie-Mellon Univ., Pittsburgh, Pa. Metals Research Lab.
ALLOY DESIGN TO RESIST HYDROGEN EMBRITTLEMENT
I. M. Berstein and A. W. Thompson (Rockwell Intern. Corp., Thousand Oaks, Calif.) 21 Nov. 1974 87 p refs Submitted for publication
(Contract N00014-67-A-0314-0019; NR Proj. 036099)
(AD-A002274; TR-3; CMU-036-099-3) Avail: NTIS CSCL 11/6

The behavior of steel, titanium, aluminum and nickel alloys are analyzed in terms of the specific interrelationships between metallurgical variables and the susceptibility towards hydrogen embrittlement. It is demonstrated that specific recommendations can be made which should improve the performance of a given material in a hydrogen-bearing or producing environment. These recommendations are balanced with nonenvironmental strength and toughness constraints, since little progress would be made, for example, by changing an alloy from hydrogen-embrittlement-critical to toughness-critical in a given design environment. GRA

N75-19436# Frankford Arsenal, Philadelphia, Pa.
DEVELOPMENT OF INTENSIOSTATIC-GALVANIC STRESS CORROSION TEST FOR HIGH STRENGTH ALUMINUM ALLOYS
Joseph J. Gordon and James V. Rinnovatore Mar. 1974 15 p refs
(AD-A002599; FA-M74-6-1) Avail: NTIS CSCL 11/6

An investigation was performed to identify improved methods for determining the stress corrosion resistance of strain hardenable 5083 alloy and heat-treatable high strength 7075 and 7050 alloys. An intensiostatic test method was investigated for strain hardenable 5083 alloy and the results showed that the test is capable of discriminating among conditions which have small differences in susceptibility to stress corrosion. The improvement in the sensitivity of the intensiostatic test as compared to the conventional alternate immersion test is shown to be significant. In addition, the test is more rapid than the conventional alternate immersion test. A galvanic test method was investigated for two copper bearing high strength aluminum alloys, 7075 and 7050. The results showed that the galvanic test is capable of discriminating among various tempers of the alloys which possess a wide range of stress corrosion susceptibility. The test is also more rapid than the conventional alternate immersion test. GRA

N75-21837# National Environmental Research Center, Research Triangle Park, N.C.
AIR POLLUTION EFFECTS ON CATASTROPHIC FAILURE OF METALS
Jon Gerhard and Fred H. Haynie Nov. 1974 39 p refs
(PB-238290/1; EPA-650/3-74-009) Avail: NTIS HC $3.75 CSCL 13B

Air pollutants contribute to the catastrophic failure of metal structures through the mechanisms of stress-corrosion cracking, corrosion fatigue, and hydrogen embrittlement. The 'Silver Bridge' catastrophe, LORAN tower parts failures, aircraft parts failures resulting in accidents, and communications equipment failures are examples cited that were related to air pollution. An economic analysis of these failures indicated that accompanying injury and loss of life is an annual economic loss to the nation of from $50 million to $100 million. GRA

N75-26116# Martin Marietta Aerospace, Denver, Colo.
THE INFLUENCE OF ENVIRONMENT ON CRACK BEHAVIOR Final Report
I. R. Kramer Aug. 1974 23 p refs
(Contract F44620-74-C-0032; AF Proj. 9782)
(AD-A003954; MCR-74-143-F; AFOSR-74-1908TR) Avail: NTIS CSCL 11/6

The analytical expressions presented in this report relate the crack velocity and the failure time to the surface-layer stress coefficient for compact-tension specimens of Ti-6Al-4V and a 4130 steel subjected to stress-corrosion cracking. The experimental data for the threshold stress intensity factor and the crack velocities for various stress intensity factors agree well with the calculated values. GRA

N75-26122# Dayton Univ. Research Inst., Ohio.
FRACTURE RELATED PROPERTIES OF X-2048-T851 PLATE INCLUDING SPECIMEN SIZE EFFECTS ON KIC Final Report, Sep. 1973 - Aug. 1974
G. J. Petrak Dec. 1974 37 p refs
(Contract F33615-74-C-5024; AF Proj. 7381)
(AD-A004199; UDRI-TR-74-27; AFML-TR-74-261) Avail: NTIS

Mechanical property data were developed on a new aluminum alloy that is designated as X2048. The material, which was tested in the -T851 condition, was developed by its manufacturer, Reynolds Aluminum, to possess the strength, fatigue resistance, thermal stability and corrosion resistance of 2024-T851 and 2124-T851 while at the same time having increased toughness. It was shown that the strength and fatigue crack growth rate of X2048 are the same as 2024 and 2124 and that the X2048 possesses increased toughness. A limited corrosion study using precracked specimens showed the material to be unaffected by a salt water environment under the test conditions. The room temperature fracture test results were dependent on specimen size with larger specimens producing higher fracture toughness test data. Fracture toughness test data from the literature that was obtained using bend specimens were lower than the fracture toughness results obtained in this effort which employed compact tension specimens. GRA

N75-32186# Naval Air Development Center, Warminster, Pa. Air Vehicle Technology Dept.
EFFECTS OF GRAPHITE-EPOXY COMPOSITE MATERIALS ON THE CORROSION BEHAVIOR OF AIRCRAFT ALLOYS
P. Fischer and J. DeLuccia 3 Apr. 1975 38 p refs
(AD-A010127; NADC-75031-30) Avail: NTIS CSCL 11/6

The electrochemical approach was used to show the nature of the galvanic corrosion when graphite-epoxy composite materials are coupled to aluminum and titanium alloys. An open circuit potential difference of one volt was obtained in 3.5% NaCl solution between the composite and 7075-T6, 7075-T651 and 5052-

H38 alloys. This potential difference provides a driving force for corrosion and is cause for concern. The Ti-6-4 showed a difference of about 0.3 volt for the unpolished as received material. Corrosion current data (zero impedance technique) indicate that aluminum alloys and cadmium plate are much more reactive than Ti-6-4 when coupled to graphite-epoxy. This technique provides a means of ranking the severity of this corrosion problem for various aircraft alloys. Flatwise tensile data indicate significant strength losses when graphite-epoxy composite sandwich specimens are exposed to ASTM 5% salt spray and synthetic sea water - SO2 spray environments. GRA

N75-32227# Imperial Coll. of Science and Technology, London (England). Dept. of Metallurgy and Materials Science.
PRE-EXPOSURE EMBRITTLEMENT AND STRESS CORROSION FAILURE IN HIGH STRENGTH Al-Sn-Mg ALLOYS Final Technical Report, 12 Jan. 1974 - 11 Jan. 1975
Geoffrey M. Scamans, Reza Alani, and Peter R. Swann Feb. 1975 29 p refs
(Grant DA-ERO-124-74-G0033; DA Proj. DO1-61102-B-32D)
(AD-A010491) Avail: NTIS CSCL 11/6

It has been found that a high purity Al-6%Zn-3%Mg alloy becomes embrittled if pre-exposed to moist gases prior to tensile testing. The degree of embrittlement increases with the time of pre-exposure and with the temperature and relative humidity of the pre-exposure environment. The alloy is most sensitive to embrittlement when solution treated at 475C but this sensitivity can be reduced considerably if the surface film formed at 475C is removed by electropolishing. The embrittlement is not strain rate sensitive and the ductility of the pre-exposed alloy cannot be recovered by storing unstressed in dry air or in vacuo. However, the ductility of embrittled specimens can be fully restored if tensile testing is carried out under vacuum. If 1.7% copper or 0.14% chromium are added to the high purity alloy the rate of embrittlement is reduced and is even more reduced in the commercial 7075 alloy. GRA

N75-33248# Naval Ship Research and Development Center, Bethesda, Md. Materials Dept.
ENHANCEMENT OF FATIGUE, CREEP, AND STRESS-CORROSION RESISTANCE BY SURFACE TREATMENTS
I. R. Kramer Jun. 1975 30 p refs Submitted for publication
(AD-A011038; NSRDC-4546) Avail: NTIS CSCL 13/8

By considering the nature of the surface layer formed as a result of plastic deformation, substantial improvements may be made in the fatigue, creep, and stress-corrosion cracking resistance. When the surface layer stress is decreased, the fatigue and stress-corrosion cracking resistance is increased. When its relaxation rate is decreased, the creep rate is also decreased. GRA

N76-10308# Rensselaer Polytechnic Inst., Troy, N.Y. Dept. of Materials Engineering.
CORROSION FATIGUE OF Cu AND Cu 7.8% Al Final Report, 1 Mar. - 31 Aug. 1974
D. J. Duquette Dec. 1974 10 p refs
(Contract DAHC04-74-C-0015)
(AD-A011398; ARO-12091.1-MS) Avail: NTIS CSCL 11/6

Transmission electron microscopy of pure copper exposed to air and to corrosive solutions under cyclic stresses shows that corrosion effectively softens metal surfaces by destroying the dislocation cell structure and preventing its reformation, thus resulting in accelerated slip. Additionally the preferential corrosion of surface slip offsets and grain boundaries results in grooving of these areas and rapid intergranular crack initiation and similarly studies of Cu 7.8% Al alloy single crystals shows corrosion to be specifically associated with surface slip offsets. GRA

N76-12146# Aerospace Corp., El Segundo, Calif. Lab Operations.
THE CORROSION OF 6061 ALUMINUM ALLOY-THORNEL 50 GRAPHITE COMPOSITE IN DISTILLED WATER AND NaCl SOLUTION Interim Report
Dennis L. Dull, William C. Harrigan, Jr., and Maurice F. Amateau 6 May 1975 21 p refs
(Contract F04701-74-C-0075)
(AD-A011761; TR-0075(5621)-2; SAMSO-TR-75-130) Avail: NTIS CSCL 11/4

The corrosion behavior of a 6061 aluminum alloy-Thornel 50 graphite composite has been examined in both distilled water and 3.5% NaCl solution at three temperatures: 298K (25C), 323K (50C), and 348K (75C). The corrosion rate was determined by the weight change and was monitored for times up to 1000 hr. The corrosion rates were maximum immediately after the initial immersion and decreased with increasing time of exposure. The NaCl solution was far more corrosive than the distilled water, and increasing the temperature resulted in an increased corrosion rate. The mode of attack appears to be crevice corrosion promoted by galvanic coupling between the aluminum matrix and graphite fibers. GRA

N76-14220# Flow Research, Inc., Kent, Wash.
REACTIONS AND ELECTROCHEMICAL KINETICS OF NEWLY-GENERATED METAL SURFACES Final Scientific Report, 1 May 1972 - 30 Jun. 1975
Theodore R. Beck Jul. 1975 22 p refs
(Contract F44620-72-C-0070; AF Proj. 9536)
(AD-A013843; AFOSR-75-1074TR) Avail: NTIS CSCL 07/4

Air Force flight vehicles must withstand increasingly complex environmental and operational regimes. Fundamental knowledge of the mechanisms of fatigue and fracture of flight structures is required. This research is related to the understanding of crack propagation, stress corrosion and corrosion fatigue in titanium and other metals. An electrochemical mass transport kinetic (MTK) model was previously formulated by the author to quantitatively describe the electrochemical events in a crack. The research described was done to fulfill the requirement of the model for quantitative data on new titanium surfaces and to develop a general understanding of the kinetics of the repassivation process. GRA

N76-14248# American Univ., Washington, D.C. Dept. of Chemistry.
STRESS CORROSION CRACKING CONTROL MEASURES. 4: ALUMINUM ALLOYS
B. F. Brown Jun. 1975 40 p refs
(Contract N00014-68-A-0247-0007; NR Proj. 036-103)
(AD-A013611) Avail: NTIS CSCL 11/6

The most prevalent form of SCC service failures in aluminum alloys is caused by a combination of water, aqueous solutions or atmospheric moisture, alloy of susceptible composition and structure, and sustained tensile stresses, most often caused by heat treatment or assembly. The principal practical measures to control SCC are: (1) select an alloy of minimum susceptibility; (2) for wrought alloy, take precautions not to impose high sustained stresses across the short transverse grain direction unless the alloy and temper confer low susceptibility; (3) keep water and water vapor from the metal surface by providing natural drainage and by painting, with an inhibitor such as chromate; (4) minimize opportunities for chlorides to concentrate; (5) when using a susceptible alloy and temper, compressively stress the metal surface by peening or rolling, followed by painting; (6) use cathodic protection; (7) do not permit mercury or its compounds in close proximity to any aluminum structure. GRA

N76-14249# American Univ., Washington, D.C. Dept. of Chemistry.
STRESS CORROSION CRACKING CONTROL MEASURES. 5: TITANIUM ALLOYS
B. F. Brown Jun. 1975 25 p refs
(Contract N00014-68-A-0245-0007; NR Proj. 036-103)
(AD-A013612) Avail: NTIS CSCL 11/6

The practical SCC hazards to titanium involve a wide range of environments. For some groups of environments, such as natural waters and nearly neutral aqueous solutions, the cracking occurs only in the presence of a pre-existing crack-like flaw, and fracture mechanics type tests readily characterize the SCC behavior of alloys. Unalloyed titanium and the widely used Ti-6%al-4%V alloy are reasonably resistant to SCC in these environments. For N2O4 and red fuming nitric acid, practical control of the problem is available through controlling the composition of the oxidizers, for which standard specifications are available. For the hot salt cracking problem during heat treatment, meticulous cleanliness of the titanium, backed up preferably by excluding moisture and oxygen from the heat treating atmosphere, serves to control the problem. Though untried in practice, a nickel barrier paint may be useful when contamination at elevated temperatures cannot be avoided in service; the alternative is to design for low operating stresses. For some environments, such as methanol, mercury, cadmium or silver, the strategy is to exclude them from titanium surfaces. GRA

N76-14250# Frankford Arsenal, Philadelphia, Pa.
CORRELATION DETERMINATIONS BETWEEN STRESS CORROSION CHARACTERISTICS OF WROUGHT 7039 ALUMINUM ARMOR AND OTHER ALLOY CHARACTERISTICS: BALLISTIC PERFORMANCE, YIELD STRENGTH, AND ELECTRICAL CONDUCTIVITY
James V. Rinnovatore, Donald T. Rorabaugh, and Albert Zalcmann Apr. 1975 31 p ref
(DA Proj. 1G6-62601-AH-71)
(AD-A013981; FA-TR-75026) Avail: NTIS CSCL 19/4

The study was performed to determine whether a correlation could be established between the stress corrosion resistance of wrought 7039-T6 aluminum armor plates and other alloy characteristics such as ballistic performance, yield strength, and electrical conductivity. A survey and statistical analysis were conducted on acceptance test data available for about 500 preproduction lots of 7039-T6 plates. GRA

N76-15294# Rensselaer Polytechnic Inst., Troy, N.Y. Dept. of Materials Engineering.
HYDROGEN ASSISTED FATIGUE CRACKING OF HIGH STRENGTH ALUMINUM ALLOYS
E. F. Smith, III, R. Jacko, and D. J. Duquette Aug. 1975 27 p refs
(Contracts N00014-67-A-0117-0012; N00014-75-C-0466; NR Proj. 036-093)
(AD-A014477) Avail: NTIS CSCL 11/6

High cycle tension-tension fatigue tests have been performed on a 7075-T6 alloy in air, in 0.5N NaCl, pre-corroded in 0.5N NaCl, re-heat-treated and tested in air. Additionally fatigue tests were performed on a high purity analogue alloy, (Al-5.5Zn 2.5Mg-1.5Cu) in air, in 0.5N NaCl and in NaCl with applied cathodic currents (hydrogen charged). Corrosion fatigue of the high-purity alloy resulted in intergranular crack initiation with a shift to transgranular cracking as the crack propagated. High charging currents and high cyclic stresses tended to reduce the relative amount of intergranular cracking. Transgranular fatigue fracture surfaces differed from those observed in air tests in that they were highly faceted (crystallographic) and exhibited cleavage-type markings. These results indicate that corrosion fatigue of high-strength aluminum alloys is a hydrogen embrittlement process with hydrogen being produced by corrosion of the alloy. Transgranular cracking occurs when high cyclic stresses induce mobile dislocations which cause hydrogen migration into the grains in fatigue-generated slip bands. GRA

N76-15305# Dayton Univ. Research Inst., Ohio.
STATIC AND DYNAMIC FRACTURE PROPERTIES FOR ALUMINUM ALLOY 7475-T651 AND T7351 Final Report, Oct. 1973 - Dec. 1974
R. R. Cervay Apr. 1975 38 p refs
(Contract F33615-74-C-5024; AF Proj. 7381)
(AD-A014353; AFML-TR-75-20) Avail: NTIS CSCL 11/6

A broad base of mechanical property data were developed on two plates of Al 7475. One of the 1-1/2-inch thick plates was in the T7351 condition and one was in the T651 condition. The tensile properties of the T651 plate were higher than those of the T7351 plate. Nearly all of the fracture toughness tests were invalid by ASTM test standards; those that were valid indicate the material possesses good toughness. The conditional toughness values (K sub Q) for identical test conditions indicate the T7351 processing possesses the superior toughness property. The smooth and notched fatigue properties were about equal to those of other 7000-series aluminum alloys. Constant amplitude fatigue crack growth resistance was better than some older 7000-series alloys and similar to other new 7000-series alloys while the stress corrosion cracking properties in a salt water environment were excellent. Most of the tests were repeated using specimens that had been subjected to 250 F (121 C) for 1000 hours. This time-temperature exposure resulted in: (1) a slight reduction in tensile strength, (2) a slight increase in conditional toughness (K sub Q) for the T651 plate and a small decrease in K sub Q for the T7351 heat treated plate, (3) a slight reduction in fatigue properties, and (4) negligible effect on the fatigue crack growth rate and corrosion properties.
Author (GRA)

N76-15308# Martin Marietta Labs., Baltimore, Md.
THE INFLUENCE OF LOADING MODE ON THE STRESS CORROSION SUSCEPTIBILITY OF VARIOUS ALLOY/ENVIRONMENT SYSTEMS Interim Technical Report
J. A. S. Green, H. W. Hayden, and W. G. Montague Aug. 1975 35 p refs
(Contract N00014-74-C-0277; NR Proj. 031-716)
(AD-A014611; MML-TR-75-30C) Avail: NTIS CSCL 11/6

The influence of loading mode on stress-corrosion susceptibility has been examined for the following systems: Ti- 8Al 1Mo 1V alloy/aqueous chlorides; alpha - brass/ammoniacal environments, 7075-T6 Al alloy in NaCl/K2Cr2O7 solutions. With the exception of the alpha- brass/ammonia system, the stress-corrosion susceptibility of the metals was found to be much greater under tensile (mode I) loading than torsional (mode III) loading. Further, in certain instances the addition of hydrogen-recombination (cathodic) poisons, i.e., arsenic, was found to enhance susceptibility to cracking as a function of loading mode is interpreted to indicate that hydrogen damage is the dominant mechanism leading to failure. Implications of these results to mechanistic understanding are discussed. GRA

A73-43466 # **Improvement of the corrosion-fatigue strength of aluminum alloys by exposure of the medium to a magnetic field (Povyshenie korrozionno-ustalostnoi prochnosti aliuminievogo splava pri obrabotke sredy magnitnym polem).** A. V. Karlashov and I. I. Priakhin (Kievskii Institut Inzhenerov Grazhdanskoi Aviatsii, Kiev, Ukrainian SSR). *Fiziko-Khimicheskaia Mekhanika Materialov*, vol. 9, no. 4, 1973, p. 23-26. 7 refs. In Russian.

A 7000-Oe unipolar constant magnetic field was applied to corrosive media (3% aqueous solution of NaCl, fresh water, and a petroleum fuel) flowing at 0.5 m/sec. The test temperature was 20 C and the usable length 100 mm. It is shown that the fatigue strength in pure bending of aircraft aluminum 2-mm sheet samples exposed to the magnetized medium was greater than in the absence of a magnetic field. V.P.

A74-24297 # **Study of the speed of fatigue crack propagation in the case of light alloys and titanium alloys (Etude de la vitesse de propagation des fissures de fatigue dans le cas des alliages légers et des alliages de titane).** G. Sertour and G. Hilaire (Société Nationale Industrielle Aérospatiale, Suresnes, Hauts-de-Seine, France). In: Fatigue: Relations between metallurgical and mechanical aspects; Conference on Metallurgy, 15th, Saclay, Essonne, France, June 21, 22, 1972, Proceedings. (A74-24287 10-17) Gif-sur-Yvette, Essonne, France, Institut National des Sciences et Techniques Nucléaires, 1973, p. 337-354. In French.

A74-44538 # **Effects of corrodents on the fatigue life of an ultra-high strength steel.** J. Y. Mann and D. S. Kemsley (Department of Supply, Aeronautical Research Laboratories, Melbourne, Australia). In: Effects of chemical environment on fracture processes; Proceedings of the Third Tewksbury Symposium, Melbourne, Australia, June 4-6, 1974. (A74-44526 23-17) Melbourne, University of Melbourne, 1974, p. 207-220. 8 refs.

Notched SAE 4340 steel specimens of UTS 1570 MPa were fatigue-tested to fracture in repeated tension under a four-load-level program-loading sequence in very dry air and in seven 'aggressive' environments - wet air; four processing liquids in either dry or wet air; distilled water; and 3% NaCl solution. Fatigue lives ranged from 53 programs (dry air) to 1 program (wet air plus phosphoric acid). Fractographic examination showed that in some instances crack initiation was unaffected, but crack propagation was rapid, whereas in some other instances the reverse was the case. Fatigue crack propagation rates alone are thus insufficient to predict total fatigue lives. (Author)

A75-20448 # **Solubility of hydrogen in molybdenum and its alloys.** T. Eguchi and S. Morozumi (Tohoku University, Sendai, Japan). *Japan Institute of Metals, Journal*, vol. 38, Nov. 1974, p. 1019-1025. 26 refs. In Japanese, with abstract in English.

Solubility of hydrogen at one atmosphere of pressure in molybdenum and its binary solid solution alloys containing titanium, zirconium, vanadium, and niobium respectively was measured in the 600-1200 C range. Various results correlating solubility with temperature, alloy composition, relative partial molar entropy and enthalpy, specific heat coefficient, lattice strain induced by alloying, and vibrational frequency of the hydrogen atom are presented. S.J.M.

N74-72907 McDonnell-Douglas Corp., Long Beach, Calif. Aircraft Div.

EVALUATION OF HIGH STRENGTH STEELS FOR HEAVY SECTION APPLICATIONS Engineering Technical Report
C. V. Thrash Nov. 1965 145 p
(AD-772417; DAC-LB-32437)

Static and dynamic properties of these high strength steels were determined: marage 250, marage 300, HP 9 Ni-4 Co-45C (martensitic), HP 9 Ni-4Co-45C (bainitic), 4340 (260 to 280 ksi), 4330v and Hy-Tuf. The properties investigated were: tensile and notch tensile; axial fatigue, notched (K sub t = three) and unnotched (K sub t = one); fracture toughness, face crack and through crack; charpy v-notch impact; resistance to hydrogen embrittlement cracking; sustained load and resistance to stress corrosion cracking. Modified Author Abstract

N75-77588 Battelle Columbus Labs., Ohio.
SUBCRITICAL CRACK GROWTH UNDER SUSTAINED LOADING AS EFFECTED BY STRESS MODE AND CORROSIVE ENVIRONMENT Final Scientific Report
Dean N. Williams Jul. 1974 13 p
(Contract AF-AFOSR-2283-72; AF Proj. 9761)
(AD-783263; AFOSR-TR-74-1223)

Subcritical crack growth under sustained load in a Ti-4Al-3Mo-1V alloy has been investigated using compact tension specimens under constant load. Crack growth sufficient to cause failure in less than one week was observed at initial stress intensities as low as 0.45 K sub c. Subcritical crack growth was not attributable to stress corrosion; it occurred more readily in vacuum than in salt water. Since the alloy was stabilized in vacuum prior to test, metallurgical instability also appears an unlikely contributory factor. Tests of specimens of several thicknesses having variable degrees of triaxial loading across the crack front suggest that subcritical crack growth is controlled by the combined influences of creep in the uncracked surface region under plane stress loading and strain-dependent plane strain fracture in the central region and triaxial loading.
Modified Author Abstract

N75-77861 Naval Air Development Center, Warminster, Pa. Air Vehicle Tech. Dept.
THE EFFECTS OF CHROMATE CONVERSION COATING ALUMINUM STRESS CORROSION SPECIMENS Progress Report
I. S. Shaffer Mar. 1974 16 p
(AD-777031; NADC-74041-30)

A major problem in assessing stress corrosion susceptibility of 7XXX series aluminum alloys by alternate immersion in a 3.5 percent NaCl aqueous solution is excessive pitting corrosion. An investigation was initiated to determine if chromate conversion surface treatment would improve the sensitivity of the alternate immersion test by minimizing pitting and gross corrosion. Results of alternate immersion tests of coated and bare 7075 tensile bar and C-ring specimens showed that stress corrosion cracks were easier to detect on chromate conversion coated specimens. Author

N75-78005 Air Force Materials Lab., Wright-Patterson AFB, Ohio.
HYDROFLUOROCARBON SEALANTS WITH IMPROVED LOW TEMPERATURE AND STRESS CORROSION PROPERTIES Final Report, Jan. 1969 - Nov. 1972
W. F. Anspach Nov. 1974 40 p
(AF Proj. 7340)
(AD-A006161; AFML-TR-72-290; GIDEP-501.90.00.00-G7-01)

Hydrofluorocarbon integral fuel tank sealants have been prepared which exhibit significantly improved low temperature and stress corrosion properties. This report discusses compounding effects, evaluation of adhesion enhancement techniques and a basic investigation of the stress corrosion susceptibility of titanium substrates in contact with the sealants and compounding ingredients contained in them. Data is presented and discussed which demonstrates both the advantages and limitations of these fuel tank sealing materials. Resin primers look very promising and when used with the AFML hydrofluorocarbon sealants described here, produce a bond to titanium substrates which is completely satisfactory in that it equals or exceeds the cohesive strength of the sealant.

76-06001 Grumman Aircraft Engineering Corp., Bethpage, N.Y.
EFFECT OF MICROSTRUCTURE AND ENVIRONMENT ON STRESS CORROSION OF 7075 ALUMINUM ALLOY Research Report
G. Geschwind and P. N. Adler Jan. 1973 29 p
(AD-756236; RM-564J)

Grain boundary microstructure as well as the ph in a chloride ion solution environment was found to be significant to stress corrosion attack in 7075 aluminum alloys. The influence of these factors on both the initiation and propagation of cracking and the mode of attack in these alloys are described. Microstructural modifications to attain desirable stress corrosion resistance are suggested. Author

76-06002 Alpha Research and Development, Inc., Elverson, Pa.
THE EFFECTS OF COMPOSITION, ENVIRONMENT AND STRESS ON THE DURABILITY OF COMPOSITE BONDS Final Report, 10 Mar. 1971 - 10 Mar. 1972
R. L. Patrick, J. A. Brown, and L. Dunbar Mar. 1972 45 p
(Contract N00019-71-C-0277)
(AD-762080)

It was shown that a single recrystallization of m-phenylenediamine (MPDA) was most effective in generating optimum crack propagation values in the MPDA cured epoxy system. It was also shown that stoichiometric quantities (14.5 phr) of MPDA provided the highest crack propagation values. Fillers were examined and a flat platelets (aluminum silicate) and rounded, granular (zirconium silicate) particles were utilized at various particle sizes and concentrations. The highest crack propagation value was obtained at 50 phr with the 1.5 micron aluminum silicate. As the size of the filler particles increased, crack propagation approached, indicating that large particles were more effective as crack stoppers in filled adhesive systems. Author

76-06003 Rensselaer Polytechnic Inst., Troy, N.Y.
CORROSION FATIGUE CRACK INITIATION IN Cu AND Cu 7.8 PERCENT Al
D. Dequette, P. Andresen, and H. Masuda 1973 8 p Pub. in unidentified journal
(Contract DAHC04-71-C-0022; DA Proj. 2-0-061102-B-32-D)
(AD-770209; AROD-9741:2-MC)

The origin of corrosion fatigue cracking has generally been associated with either pitting, various forms of stress assisted dissolution or localized film rupture. To date most studies of corrosion fatigue have concentrated on the examinations of cycles to failure data or on post failure observation of cracking. An important exception to this type of examination has been the work of Forsyth in high strength aluminum alloys. The present study outlines an investigation on the effect of slip character on corrosion fatigue crack initiation by comparing the surface characteristics of a wavy slip material (Cu) with a planar slip material (Cu-7.8 percent Al) exposed to cyclic stresses and aggressive environments. Modified Author Abstract

76-06004 Frankford Arsenal, Philadelphia, Pa.
STRESS CORROSION SUSCEPTIBILITY OF ALUMINUM CARTRIDGE CASES Technical Research Report
M. A. Pelensky and A. Gallacio Sep. 1973 39 p
(DA Proj. 1-W-562604-A-010)
(AD-778737; FA-R-2091)

The report concerns the investigation of stress corrosion cracking of experimental aluminum cartridge cases in a 6 percent sodium chloride boiling solution. The cases (5.56 mm) were of 7475 aluminum alloy, tempered to T6 or T73 condition, and the empty cases assembled with projectiles to represent the stressed condition of finished cartridges. Stresses applied to the mouth rim and neck of the cases were calculated from the interference, i.e., projectile diameter vs internal diameter of the case mouth and the case neck wall thickness. For each of three calculated stress levels, a range of failure times was observed.
Modified Author Abstract

76-06005 Battelle Columbus Labs., Ohio.
SUBCRITICAL CRACK GROWTH UNDER SUSTAINED LOAD
Dean N. Williams Mar. 1974 10 p Pub. in Met. Trans., v. 5, Nov. 1974 p 2351-2358
(Contract AF-AFOSR-2283-72; AF Proj. 9761)
(AD-A006056; AFOSR-TR-75-237)

Compact tension specimens of annealed Ti-4Al - 3Mo - 1V were exposed under sustained load for periods of up to 8 days to determine the effects of initial stress intensity and test environment on subcritical crack growth. Crack growth occurred by a tunneling process with no surface crack extension until just prior to final rapid failure. Crack growth in vacuum or moist air environments occurred at stress intensities as low as 40 pct of the fracture toughness, and there was no evidence of a threshold stress intensity below which crack growth would not occur. Specimens tested in salt water behaved similarly at stress intensities of greater than about 60 pct of the fracture toughness, but showed crack arrest at lower stress intensities. At lower stress intensities, resistance to crack growth in a saltwater environment was superior to that in vacuum or moist air. Subcritical crack growth was readily identified on the fracture surface after exposure in all three environments through the presence of numerous cleavage-like facets. A critical strain concept, with crack growth occurring as a result of creep processes, can be used to explain the results. Author

76-06006 Battelle Columbus Labs., Ohio.
EFFECT OF SPECIMEN THICKNESS ON SUBCRITICAL CRACK GROWTH UNDER SUSTAINED LOAD
D. N. Williams Jul. 1974 9 p Pub. in Mater. Sci. Engr., v. 18, 1975 p 149-155
(Contract AF-AFOSR-2283-72; AF Proj. 9761)
(AD-A009691; AFOSR-TR-75-0573)

Subcritical crack growth under sustained load in annealed Ti-4Al-3Mo1V (117 K.S.I. yield strength) was measured using compact tension specimens of three thicknesses, 0.75, 0.25 and 0.13 inch. Crack growth terminating in failure occurred under constant load in all three specimens at initial stress intensities well below the critical stress intensity as measured in rising load tests. Time to failure at low initial stress intensity was considerably increased by increased mixed mode stress conditions; it was appreciably longer in 0.13 than in 0.25 inch thick specimens. However, time to failure was about the same in 0.75 inch thick specimens, tested under linear elastic plane strain conditions, as in 0.25 inch thick specimens. Specimen size affected the kinetics of crack growth and the shape of the crack surface developed under sustained load. Up to the point of final unstable failure, fracture occurred almost exclusively in material under triaxial stress, resulting in a considerable amount of crack front bowing. Author

76-06007 Flow Research, Inc., Kent, Wash.
REACTIONS AND KINETICS OF NEWLY GENERATED TITANIUM SURFACES AND RELEVANCE TO STRESS CORROSION CRACKING
T. R. Beck 1974 10 p Pub. in Corrosion-Nace, v. 30, no. 11, Nov. 1974 p 408-414
(Contract F44620-72-C-0070; AF Proj. 9536)
(AD-A010302; AFOSR-TR-75-0523)

Instrumentation is described for obtaining current-time curves for new metal surfaces produced by fast fracture in electrolytes under potentiostatic conditions. Measured anodic current densities for titanium specimens in acid solutions decayed about a million fold in a time of .0001 to 1000 sec at which steady state was approached. Analysis of the experimental data indicates the actual initial current density for anodic dissolution is more than 10 A/sq cm in 3M HCl and may be orders of magnitude greater. Thus stress corrosion crack propagation by an anodic process in titanium cannot be ruled out. Formation of metal salt films would be predicted at high anodic current densities in cracks. Calculations show that formation and growth of a salt film in the tip region would give a rapidly decaying current density moving away from the tip which would keep the tip sharp. This phenomenon may be called the electrochemical knife. Author

76-06008 Naval Air Development Center, Warminster, Pa. Air Vehicle Technology Dept.
STRESS CORROSION RESISTANCE OF 7050-T73 ALUMINUM ALLOY Progress Report
I. Shaffer Sep. 1975 13 p
(AD-A015966; NADC-75205-30)

The objective of this investigation was to evaluate the stress corrosion behavior of the 7050 aluminum alloy in the overaged T73 heat treat condition. Stress corrosion tests were conducted using both smooth and precracked specimens. No evidence of stress corrosion was found in any of the tests conducted. The material also exhibited immunity to exfoliation in both salt spray and constant immersion tests. Author

76-06009 Army Materials and Mechanics Research Center, Watertown, Mass.
MICROSTRUCTURAL EFFECTS ON THE STRESS CORROSION CRACKING BEHAVIOR OF Ti-8Al-1Mo-1V IN METHANOLIC AND CHLORIDE SOLUTIONS Final Report
Walter F. Czyrklis and Milton Levy Oct. 1975 15 p
(DA Proj. 1T1-62105-AH-84)
(AD-A018793; AMMRC-TR-75-21)

The stress corrosion cracking behavior of Ti-8Al-1Mo-1V has been studied in several environments. Of the environments employed, methanol with a small addition of hydrochloric acid was found to be the most aggressive. Altering the microstructure of the alloy produced a marked improvement in resistance to stress corrosion cracking in distilled water and salt water media. The SCC susceptibility was also significantly decreased by the addition of sodium nitrate to both salt water and methanol plus hydrochloric acid environments. Fractographic analyses have been carried out and related to SCC behavior. Author

76-01010 Hawker Siddeley Aviation Ltd., Stockport (England).
STRESS-CORROSION CRACKING AND THE AIRCRAFT INDUSTRY
J. Fielding [1973] 2 p Repr. from J. Inst. Met. (London), v. 101, Sep. 1973 p 238-240
(EI1740524271; Rept-424271)

07

WEAR

N74-33228*# National Aeronautics and Space Administration. Lewis Research Center, Cleveland, Ohio.
FRETTING IN AIRCRAFT TURBINE ENGINES
Robert L. Johnson and Robert C. Bill [1974] 17 p refs
Presented at the Specialists Meeting on Friction and Wear in Aircraft Systems, Munich, 11-12 Oct. 1974; sponsored by AGARD
(NASA-TM-X-71606; E-8090) Avail: NTIS HC $3.00 CSCL 21E

The problem of fretting in aircraft turbine engines is discussed. Critical fretting can occur on fan, compressor, and turbine blade mountings, as well as on splines, rolling element bearing races, and secondary sealing elements of face type seals. Structural fatigue failures have been shown to occur at fretted areas on component parts. Methods used by designers to reduce the effects of fretting are given. Author

N76-10485# Naval Air Propulsion Test Center, Trenton, N.J.
EVALUATION OF MIL-L-23699 LUBRICANT PERFORMANCE IN THE TF41-A-2 ENGINE Final Report
Frank Feinberg May 1975 23 p refs
(AD-A011441; NAPTC-PE-59) Avail: NTIS CSCL 11/8

An evaluation was made of the service performance characteristics of MIL-L-23699B oils in TF41-A-2 engines. Operational experience and problems as well as the condition of the lubricant wetted engine components at overhaul are discussed. Recommendations are made concerning the expected life of MIL-L-23699B oils in the TF41-A-2 engine. GRA

A74-16696 **Evaluation of methods for reducing fretting fatigue damage in 2024-T3 aluminum lap joints.** J. P. Sandifer (Lockheed-California Co., Burbank, Calif.). *Wear*, vol. 26, Dec. 1973, p. 405-412. 7 refs.

Fatigue strength of aluminum lap joints subjected to fretting can vary widely, depending on the type of treatments applied to the faying surfaces. Many materials normally selected for their lubricity or good wear properties cannot be used in a bolted joint because of their interference with the load transfer requirements of the joint. Thus the best methods found in this evaluation in order of their effectiveness were bonded and shot-peened, bonded alone, shot-peened alone, and bonded steel wear pads. These techniques increased the fatigue strength at 10,000,000 cycles of an untreated joint from 12 ksi to a maximum of 23 ksi. (Author)

A74-28677 **Effect of metallic wear on synthetic lubricant deposition.** J. P. Cuellar and B. B. Baber (Southwest Research Institute, San Antonio, Tex.). *American Society of Lubrication Engineers, Annual Meeting, 29th, Cleveland, Ohio, Apr. 28-May 2, 1974, Preprint 74AM-1A-2.* 7 p. Members, $1.50; nonmembers, $2.00. Contract No. F33615-72-C-1097.

A special test method was utilized to study the effect of wear metal generation on deposit ratings. The concentration of iron in the test lubricant and in the principal deposits was monitored by atomic absorption spectroscopy. A direct indication of the extent of wear metal generation was provided by weight loss measurements of spring-loaded mild steel wear plates mounted within the test-lubricant sump. Significant deposit rating increases were found in many instances, depending upon the test lubricant and magnitude of wear. It is concluded that a knowledge of the inherent wear process is imperative in any definitive study of lubricant deposition. (Author)

A75-15320 # **Enhancement of wear resistance of aircraft parts (Povyshenie iznosostoikosti detalei samoletov).** K. A. Krylov. Moscow, Izdatel'stvo Transport, 1974. 144 p. 99 refs. In Russian.

The present work examines the causes of insufficient wear resistance of the rubbing parts in the hinge and pin joints of aircraft undercarriages, the valves and piston pairs of hydraulic, oil, and fuel system assemblies, and the slotted parts of engines and other assemblies. Results of studies of the conditions for excessive wear in those parts are presented. The nature of fretting corrosion and its effect on the durability of aircraft parts is investigated. Recommendations are made for the reduction of various kinds of wear in aircraft parts. P.T.H.

08

GENERAL AND GALVANIC CORROSION

N73-25621# Air Force Systems Command, Wright-Patterson AFB, Ohio. Foreign Technology Div.
THE EFFECT OF PRELIMINARY HEAT TREATMENTS ON THE CORROSION OF TITANIUM ALLOY TVO
O. M. Shapovalova, L. P. Kurilekh, and E. L. Kainenshchik 12 Apr. 1973 17 p refs Transl. into ENGLISH from Sb. Tr. Met. Khim. Titana (USSR), no. 5, 1970 p 90-99
(AD-759626; FTD-MT-24-1712-72) Avail: NTIS CSCL 11/6
The report gives the results of investigation of the effect of quenching on the corrosion of secondary titanium alloy (TVO). GRA

N74-15196# Naval Research Lab., Washington, D.C.
CORROSION CHARACTERIZATION AND RESPONSE TO CATHODIC PROTECTION OF EIGHT WIRE ROPE MATERIALS IN SEA WATER Final Report
T. J. Lennox, Jr., R. E. Groover, and M. H. Peterson 12 Sep. 1973 56 p refs
(AD-767924; NRL-7584) Avail: NTIS CSCL 11/6
The corrosion behavior and response to cathodic protection from zinc anodes have been studied on eight wire-rope materials during 790 days exposure in sea water at the NRL Marine Corrosion Research Laboratory, Key West, Florida. The titanium alloy 13V-11Cr-3Al, the nickel-base alloy, and the aluminized steel were inherently corrosion resistant. Based solely on corrosion resistance, their use would be suitable for two years total immersion in sea water even without cathodic protection. Unprotected phosphor bronze, galvanized steel, and copper-nickel clad stainless steels are not suitable for extended use in sea water. Phosphor bronze and galvanized steel would be satisfactory for long-term service if cathodically protected. The 90/10 copper-nickel clad Type 304L stainless steel was essentially corrosion free when cathodically protected. Pitting was not eliminated on unclad Type 304L stainless steel even when cathodically protected. The 90/10 copper-nickel clad Type 205 stainless steel showed localized corrosion on some of the wires when cathodically protected with a zinc anode. (Modified author abstract) GRA

N74-15203# Air Force Systems Command, Wright-Patterson AFB, Ohio. Foreign Technology Div.,
THE BEHAVIOR OF TITANIUM BASE ALLOYS IN THE AGGRESSIVE MEDIA OF SYNTHETIC RESIN PRODUCTION
S. L. Lelchuk and G. K. Grell 16 Oct. 1973 6 p Transl. into ENGLISH from Novyi Konstruktsionny Mater. (Titan), 1972 p 192-193
(FTD Proj. 60107; FTD Proj. T74-01-10)
(AD-769046; FTD-HT-23-157-74) Avail: NTIS CSCL 11/6
An alloy of titanium with 32% Mo was tested for corrosion resistance under production conditions for synthesizing bisphenol A. The resultant data show that it is corrosion resistant and can be used as a structural material for the reactor in the production of bisphenol A. Titanium alloy with 32% Mo and titanium with 5% Ta were tested under experimental conditions for synthesizinG VBFS-4 resin. Both alloys were corrosion resistant and can also be used as structural materials in the production of VBFS-4 resin. GRA

N74-16241# Air Force Systems Command, Wright-Patterson AFB, Ohio. Foreign Technology Div.
THE POSSIBILITY OF USING TITANIUM ALLOYS IN EQUIPPING A CHEMICAL COMBINE
F. N. Tavadze, T. M. Dvali, S. N. Mandzhgaladze, E. M. Strikha, and N. D. Darchiya 5 Nov. 1973 33 p refs Transl. into ENGLISH from the monograph "Novyy Konstruktsionny Material - Titan" 1972 p 206-220
(AD-769564; FTD-HT-23-162-74) Avail: NTIS CSCL 11/6
The corrosion behavior of certain titanium alloys in industrial sulfate solutions and sulfate-containing media was examined in order to study the possibility of using titanium in equipment for a caprolactam plant in a chemical combine. The corrosion resistance of the titanium alloys was determined by the gravimetric method. Tests were conducted in simulated conditions, and also directly under conditions of operation of the following equipment. GRA

N74-17261# Air Force Systems Command, Wright-Patterson AFB, Ohio. Foreign Technology Div.
CORROSION AND ELECTROCHEMICAL BEHAVIOR OF ALLOYS OF THE Ti-Mo-Cr SYSTEM IN SOLUTION OF ACIDS
N. D. Tomashov and Yu. S. Ruskol 29 Oct. 1973 11 p refs Transl. into ENGLISH from the publ. "Novyy Konstruktsionny Material - Titan" USSR, 1972 p 166-170
(AD-769994; FTD-HT-23-151-74) Avail: NTIS CSCL 11/6
The addition of chromium to alloys of the Ti-Mo system reduces the tendency toward repassivation caused by the presence of Mo. The alloy Ti-5Mo-10Cr, in the potential range 0.15-1.2 V, has the same low corrosion rate as titanium or the alloy Ti-10Cr. At potentials above 1.2 V the corrosion rate of Ti-Mo-Cr alloys increases. With an increase in Mo content from 5 to 20% in alloys of the Ti-Cr system the corrosion rate in the range of potentials of repassivation with respect to chromium increases. After the corrosion of alloys of the Ti-Mo system at potentials of repassivation, there occurs an increase in the surface layer of titanium and a decrease in molybdenum. GRA

N74-18188# Naval Research Lab., Washington, D.C.
THE EFFECT OF MERCURY AND TIN FROM ALUMINUM GALVANIC ANODES ON THE CORROSION CHARACTERISTICS OF 5086-H34 AND 6061-T6 ALUMINUM Final Report
T. J. Lennox, Jr., R. E. Groover, and M. H. Peterson 16 Nov. 1973 31 p refs
(SF51542602)
(AD-771719; NRL-7648) Avail: NTIS CSCL 11/6
Corrosion behavior studies were conducted in seawater for 696 days. There were no indications that corrosion products from either the Al-Hg-Zn or the Al-Sn-Zn galvanic anodes caused increased corrosion. Neither Hg nor Sn was found, by electron microprobe analysis, at corroded areas. The electron microprobe did reveal that the most severe localized corrosion occurred where copper, the source of which was unknown, had redeposited on the structural aluminum specimens. Cathodic protection from either the Al-Hg-Zn or the Al-Sn-Zn anodes virtually eliminated corrosion on the 5086-H34 and 6061-T6 aluminum specimens that were either continuously or alternately immersed in seawater, except for slight corrosion under some of the anodes. As expected, cathodic protection was only partially effective when it was provided for only the first 186 days of the 696 days of exposure. The slight corrosion and the buildup of bulky corrosion products between the anodes and the specimens confirmed the advisability of using some type of a barrier, such as zinc oxide paste or an organic coating, between aluminum anodes and the structure on which they are mounted. (Modified author abstract) GRA

N74-19186# Army Materials and Mechanics Research Center, Watertown, Mass.
CORROSION BEHAVIOR OF DEPLETED URANIUM-TITANIUM AND URANIUM-MOLYBDENUM ALLOYS
Milton Levy, Chester V. Zabielski, and Gilbert N. Sklover Mar. 1973 27 p refs
(DA Proj. 1T0-62105-A-349)
(AD-772958; AMMRC-TR-73-11) Avail: NTIS CSCL 11/6
The corrosion behavior of U-1.8Mo, U-3.75Mo, U-1.76Ti, U-3.41Ti, and unalloyed uranium has been studied by means of electrochemical measurements. Active-passive behavior was exhibited in sulfuric acid, sodium hydroxide, ammonium hydroxide, sodium sulfate, sodium nitrate, sodium chromate, and ammonium chromate solutions. Chloride additions as small as 0.005M destroyed passivity and caused pitting. Chromates, sulfates, and nitrates behaved as inhibitors in solutions containing low concentrations of chlorides. The uranium-molybdenum alloys were more resistant to corrosion in chloride solutions than the uranium-titanium alloys. Author (GRA)

N74-20398# Bell Aerospace Co., Buffalo, N.Y.
PROPELLANT IMPROVEMENT PROGRAM. VOLUME 1, PART 2: MODIFIED HDA STUDIES Special Technical Report, Mar. 1972 - Jul. 1973

Henry Ph. Heubusch Oct. 1973 122 p refs
(Contract F04611-72-C-0026)
(AD-773332; AFRPL-TR-73-77; Rept-8643-928004) Avail: NTIS CSCL 21/9

Three compounds were compared as replacements for HF as the corrosion inhibitor for HDA (High Density Acid). The compounds, all containing phosphorous and fluorine, were AHP (Ammonium heda fluorophosphate) PF5, and monofluorophosphoric acid. Comparison was based on results of 30-day, 90F, static corrosion tests with 6061 aluminum and 347 stainless steel. The inhibitors were tested at three or four levels of concentration and the metals were exposed separately to acid vapors and liquid. Best results were with PF5 and AHP when used in the range 0.4 to 0.6 wt %. Preference for these inhibitors over HF was further extended through 7-day tests at 120F with other metals and non-metals. In all, 26 materials were tested and the great majority were more compatible with the non-HF inhibitors. The most striking observation was reduction of stainless steels from a Class II (Short Term Usage) to a Class I (Satisfactory for General Use) rating. Analytical methods were developed in the course of the program for colorimetric determination of the corrosion inhibitor and atomic absorption determinations of iron, chromium, and nickel. (Modified author abstract) GRA

N74-21181# Army Coating and Chemical Lab., Aberdeen Proving Ground, Md.
SUBSTITUTION OF TOLYLTRIAZOLE FOR MERCAPTOBENZOTHIAZOLE IN MILITARY COOLANT INHIBITOR FORMULATIONS Interim Report
Robert G. Jamison and Charles B. Jordan Jan. 1974 27 p refs
(DA Proj. 1T6-62611-A-109)
(AD-774293; CCL-3011) Avail: NTIS CSCL 11/7

The object of this study was to determine the feasibility of substituting tolyltriazole (TT) for mercaptobenzothiazole (MBT) in the corrosion inhibitor package used in military coolants. ASTM Glassware Corrosion Tests (D 1384) and Simulated Service Tests (D 2570) were conducted on various blends of antifreeze inhibitors with different percentages of sodium tolyltriazole (NaTT). The NaTT caused foaming in the tests, but a silicone type antifoam agent was found which controlled the foaming. Results of these tests were correlated with similar tests containing the amount of MBT recommended in coolant specifications (0.4% of the sodium salt). 0.15% was found to be the optimum percentage of NaTT. GRA

N74-27027# Aerospace Corp., El Segundo, Calif. Lab. Operations.
THERMAL AND MECHANICAL EFFECTS ON THE CORROSION BEHAVIOR OF Ti-6 Al-4V Report for Jan. 1971 - Jan. 1972
Dennis L. Dull and Louis Raymond 31 Mar. 1974 32 p refs
(Contract F04701-73-C-0074)
(AD-777170; TR-0074(4250-10)-5; SAMSO-TR-74-73) Avail: NTIS CSCL 11/6

Anodic and cathodic polarization behaviors of Ti-6Al-4V were determined by potentiostatic and galvanostatic techniques in deaerated 1, 5, and 10N sulphuric acid solutions. In the active region metallurgical processing, which included cold rolling and thermal treatment, had no effect on the corrosion behavior. It is suggested that a titanium hydride film exists on the titanium alloy surface. In the passive region plastic deformation resulting from cold rolling increased the passive current density; whereas crystallographic texturing had no effect. The introduction of an alpha prime phase, resulting from thermal treatment, produced an additional peak in the passive region. Author (GRA)

N74-27058# Aerospace Corp., El Segundo, Calif.
SALT WATER CORROSION BEHAVIOR OF ALUMINUM-GRAPHITE COMPOSITE Technical Report, Apr. - Jun. 1973
E. George Kendall and Dennis L. Dull 29 Mar. 1974 18 p refs
(Contract F04701-73-C-0074)
(AD-777160; TR-0074(9250-03)-2; SAMSO-TR-74-67) Avail: NTIS CSCL 11/4

The corrosion behavior of an aluminum-graphite composite in a salt water solution has been investigated to qualitatively characterize the effect of galvanic coupling prevalent between the aluminum matrix and the graphite fibers. A comparison is made with aluminum-boron and with other materials joined to graphite blocks. Although the corrosion rate of the aluminum matrix is increased by the presence of the graphite fiber, the aluminum-graphite composite is only slightly more reactive than the aluminum-boron composite in the salt water solution. Author (GRA)

N75-11088# Battelle Columbus Labs., Ohio. Metals and Ceramics Information Center.
CORROSION OF METALS IN THE ATMOSPHERE
W. K. Boyd and F. W. Fink Aug. 1974 86 p refs
(Contract DSA900-74-C-0616)
(AD-784943; MCIC-74-23) Avail: NTIS HC $12.50 (special price)/MF $12.50 (special price) CSCL 11/6

This state-of-the-art report summarizes the main corrosion characteristics of the commercial metals commonly employed for external applications. Some of the factors that affect metal behavior in general are discussed at the outset, but since each metal has a characteristic response to the corrosive consitituents in external atmospheres, some of these factors are again discussed in the sections on the individual metals. Included in this report are sections dealing with carbon, weathering and stainless steels, aluminum-alloys, copper-base alloys, and zinc and zinc-coated steel. GRA

N75-72596 National Materials Advisory Board, Washington, D.C.
MATERIALS FOR WET OXIDATION PROCESSING EQUIPMENT (SHIPBOARD) Final Report
Nov. 1973 90 p
(Contract DA-49-083-05A-3131)
(AD-771745; NMAB-312)

The report provides an overview of the wet oxidation process and the potential materials of construction for the reaction vessel (for shipboard wastes). The wet oxidation process requires the wastes). The wet oxidation process requires the containment of corrosive products (the material being processed can range from very acidic to slightly basic and over a broad spectrum of wastes), at elevated temperatures and pressures. Wet oxidation systems can be constructed from commercially pure titanium as well as from titanium alloyed with palladium (.12-.25%). This type pf system, it is felt, can be operated safely at approximately 500F with reasonable assurance of moderate life (approximately 10 years). However, should a longer life system be desired and one which is virtually indestructible from a chemical point of view, a tantalum-lined and coated titanium system would provide the best choice of materials. Modified Author Abstract

N75-76003 Air Force Systems Command, Wright-Patterson AFB, Ohio. Foreign Technology Div.
CORROSION RESISTANCE OF TITANIUM ALLOYS IN MEDIA OF ORGANOCHLORINE SYNTHESIS
A. M. Sukhotin, A. A. Pozdeeva, G. G. Mikhailova, and N. G. Boriskina Oct. 1973 11 p Transl. into ENGLISH from the book "Novyi Konstrukt. Material-Titan" USSR, 1972 p 186-191
(FTD Proj. 60107; FTD Proj. T74-01-10)
(AD-768434; FTD-HT-23-156-74)

Titanium - Mo alloy 4201 has high corrosion resistance in media containing 10-17% hydrochloric and 10% formic acids at 100C. An increase in the corrosion resistance of titanium VT1-1 in organochlorine media in the presence of hydrochloric acid at 100C can be achieved by introducing an oxidizer, for example, 0.01-0.1% oxygen compounds of chlorine. Titanium VT1-1 and alloys 4204 and 4201 break down very rapidly in anhydrous organochlorine media in the presence of phosgene and hydrogen chloride at a temperature of about 140C.

N75-76480 Air Force Systems Command, Wright-Patterson AFB, Ohio. Foreign Technology Div.
INVESTIGATION OF THE STRUCTURE AND CORROISION BEHAVIOR OF ALLOYS IN THE Ti-Ta-Cr
N. D. Tomashov and G. P. Chernova Oct. 1973 11 p Transl. into ENGLISH from the book "Novyi Konstrukt. Material-Titan" USSR, 1972 p 158-162
(FTD Proj. 60107; FTD Proj. T74-01-10)
(AD-768433; FTD-HT-23-150-74)

Polythermal cross sections of the Ti-Ta-Cr system with a

ratio of Ta:Cr = 1:3; 1:1; 3:1 were constructed. As the tantalum content in the alloys increases the stability of the beta-phase increases and the eutectic transformation is shifted to the region of higher overall tantalum and chromium content and lowest temperatures. As the tantalum content increases the corrosion rate for both quenched and annealed alloys decreases. The ternary Ti-Ta-Cr alloys with a ratio Ta:Cr = 3:1 and binary Ti-Ta alloys with 20% or more Ta become corrosion resistant in a 5% HCl solution at 100C. Alloying titanium with chromium reduces its corrosion properties in HCl solution. The corrosion rate increases as the chromium content increases for both quenched and annealed alloys.

N75-76966 Air Force Systems Command, Wright-Patterson AFB, Ohio. Foreign Technology Div.
EXPERIENCE IN OPERATING TITANIUM EQUIPMENT IN A CHEMICAL COMBINE
V. M. Brusentsova, V. V. Kotov, Yu. I. Kalinichenko, and V. I. Symets Oct. 1973 12 p Transl. into ENGLISH from the book "Novyi Konstrukt. Material-Titan" USSR, 1972 p 203-205
(FTD Proj. 60107; FTD Proj. T74-01-10)
(AD-769322; FTD-HT-23-161-74)

The corrosion resistance of VTI brand titanium was studied in different technological media in a chemical combine. The possible areas for using titanium as the design material for preparing equipment and parts in the following production processes were determined: production of weak nitric acid; production of catalyzers, chromic acid and ferrous sulfide; production of potassium nitrate; production of ureas; production of caprolactam; and production of metaldehyde for metaldehyde solutions containing hydrochloric acid.

N75-77309 Air Force Systems Command, Wright-Patterson AFB, Ohio. Foreign Technology Div.
AN EXPERIMENT USING TITANIUM EQUIPMENT IN THE CHEMICAL INDUSTRY
Kh. L. Tseitlin and S. M. Babitskaya Oct. 1973 9 p Transl. into ENGLISH from the book "Novyi Konstrukt. Material-Titan" USSR, 1972 p 197-199
(AF Proj. 60107; AF Proj. T74-01-10)
(AD-769321; FTD-HT-23-159-74)

N75-77368 Air Force Systems Command, Wright-Patterson AFB, Ohio. Foreign Technology Div.
THE COMPATIBILITY OF TITANIUM ALLOYS WITH HYDROGEN PEROXIDE SOLUTIONS
V. M. Berenblim, L. A. Kharitonova, I. P. Yakushcheva, and Z. P. Zharikova Oct. 1973 12 p Transl. into ENGLISH from the book "Novyi Konstrukt. Material-Titan" USSR, 1972 p 193-197
(FTD Proj. 60107; FTD Proj. T74-01-10)
(AD-769320; FTD-HT-23-158-74)

Titanium, alloyed with aluminum and tin, exhibits a sharp increase in corrosion resistance, and a reduction in catalytic activity in H2O2 solutions. Thermal oxidation of titanium of VT1 grade in air increases in corrosion resistance ten-fold.

N75-77590 Air Force Systems Command, Wright-Patterson AFB, Ohio. Foreign Technology Div.
MECHANISM OF TITANIUM CORROSION IN MINERAL ACIDS AND THEIR MIXTURES
A. P. Brynza, L. I. Gerasyutina, and E. A. Zhivotovskii Oct. 1973 13 p Transl. into ENGLISH from the book "Novyi Konstrukt. Material-Titan" USSR, 1972 p 174-179
(FTD Proj. 60107; FTD Proj. T74-01-10)
(AD-768473; FTD-HT-23-153-74)

The corrosion resistance and electromechanical behavior of titanium in solutions of sulphuric, hydrochloric, and phosphoric acid in the 20-80C temperature interval were studied. It was shown that given identical solution acidity, the most aggressive with respect to titanium is sulphuric acid. The addition of sodium chloride and sulphate to phosphoric acid stimulates titanium dissolution. Sodium phosphates slow down titanium corrosion in sulphuric and hydrochloric acid slightly. The most effective in this respect is tertiary sodium phosphate. A foundation was developed for selecting a solution for the chemical removal of scale which forms on titanium at 780-820C.

N75-78069 Aerojet Liquid Rocket Co., Sacramento, Calif.
STORABILITY INVESTIGATIONS OF WATER. VOLUME 1: EXPERIMENTAL STUDIES Final Report, 15 Mar. 1972 - 15 Aug. 1973
E. M. Vanderwall, R. E. Anderson, and G. R. Janser Dec. 1973 140 p
(Contract F04611-72-C-0062; AF Proj. 3059)
(AD-772804; AFRPL-TR-73-94-Vol-1)

The objective of this program is to gather data that will permit the Air Force to assess the long-term storage characteristics of water with respect to biological growth, galvanic corrosion, and changes in composition of the water, so that the feasibility of long-term storage of water for use as a transpiration coolant can be determined. Eleven metallic and twelve nonmetallic materials are investigated. Basic fluid/material compatibility tests, galvanic couple measurements, biological growth tests, and long-term storage tests are carried out. Two types of water are used: Oxygen-saturated, deionized, filtered and oxygen-free, deionized, filtered. An extensive literature survey and critical review are conducted in conjunction with formulating the experimental portion of the program. In addition, a complete analysis is made on a LAR coolant tank in which water had been stored for 2.5 years. Author, Modified-PL

76-08001 Naval Civil Engineering Lab., Port Hueneme, Calif.
ANALYSIS OF HYDROPHONE SUPPORT STRUCTURE AFTER 52-1/2 MONTHS EXPOSURE AT A DEPTH OF 5270 FEET IN THE BARKING SANDS TEST RANGE, KAUAI, HAWAII Final Technical Note
James F. Jenkins Mar. 1973 15 p
(YF38534007)
(AD-759674; NCEL-TN-1267)

The condition of the support structure for hydrophone 4-7 of the Barking Sands Test Range, Kauai, Hawaii was analyzed after 52-1/2 months of exposure to seawater at a depth of 5270 feet. The types and severity of corrosion on the various structural components are described and analyzed. A prediction of the additional lifetime to be expected from similar structures at this location is made. Recommendations for extending the useful lifetimes of similar structures at this site are made. Author

76-08002 Frankford Arsenal, Philadelphia, Pa.
CORROSION AND CORROSION PREVENTION OF LIGHT METAL ALLOYS
Fred Pearlstein and Leonard Teitell Mar. 1973 16 p Presented at the Intern. Corrosion Forum Devoted Exclusively to the Protec. and Performance of Materials, Anaheim, Calif., Paper no. 114, 19-23 Mar. 1973
(DA Proj. 1T0-62105-A-328)
(AD-764232; FA-A73-2; Paper-114)

The corrosion rates of bare and chromated 2024-T3 aluminum and AZ31B magnesium were determined at several tropical environments (marine, open field, rain forest). Weight losses for magnesium were generally greater than for aluminum, but there were instances of catastrophic exfoliation corrosion of aluminum. Chromate conversion coatings provided effective protection to aluminum, but were only moderately protective to magnesium at the marine site, and provided no protection at nonmarine sites. The effect of environmental factors (i.e., rainfall and saltfall) on corrosion of aluminum and magnesium was studied. The effect of soil burial on corrosion rates was also determined. Double sealing (nickel acetate seal, followed by dichromate seal) of sulfuric anodized aluminum provided superior corrosion resistance over more conventional sealing techniques. Author

76-08003 Air Force Systems Command, Wright-Patterson AFB, Ohio. Foreign Technology Div.
INVESTIGATION OF THE CORROSION RESISTANCE OF ALLOYS OF THE Ti-Ta-Nb SYSTEM
N. D. Tomashov, T. V. Chukalovskaya, G. P. Chernova, P. B. Budberg, and A. L. Gavze Sep. 1973 11 p Transl. into ENGLISH from the book "Novyi Konstrukt. Material-Titan" USSR, 1972 p 162-166
(FTD Proj. 60107; FTD Proj. T74-01-10)
(AD-768472; FTD-HT-23-149-74)

The corrosion behavior of the alloys of the Ti-Ta-Nb system in 5% HCl at 100 degrees was investigated. It showed that as the Ta and Nb content in the alloy increases to 15-20% the corrosion rate drops slightly (by 1.5 to 2 times) and only upon adding alloying elements does the corrosion rate drop sharply.

Under these conditions Ta increases the corrosion resistance of the alloys more effectively than Nb.

76-08004 Summa Corp., Culver City, Calif. Hughes Helicopters Div.

EVALUATION OF THE EFFECTS OF CONTAMINATION BY SILICATES OF ANODIZING SEAL WATER Final Report, May - Jul. 1973

John M. Hogue and John French Jul. 1973 24 p
(Contract DAAJ01-73-C-0378)
(AD-768691; HH-73-44; USAAVSCOM-TR-73-11)

An evaluation of the effects of contamination by silicates in the seal water on chromic acid anodized aluminum was performed. The results of the standard salt spray test indicate that the resistance to corrosion was drastically reduced as the silicates increased above 4 parts per million. The amount of corrosion obtained was in proportion to amounts of silicates from 3 to 10 parts per million. No effect was found on adhesive bond strength as measured by T-PEEL tests, when rinsing, following chromic acid anodizing, with water containing 1 to 100 parts per million of silicate. Modified Author Abstract

76-08005 Lockheed-California Co., Burbank.

GALVANIC CORROSION EFFECTS ASSOCIATED WITH GRAPHITE COMPOSITE/METAL JOINTS

G. R. Johnson, J. S. Fritzen, and K. E. Weber Nov. 1973 32 p
(AD-776425; LR-26088; GIDEP-347.15.00.00-FB-04)

Contents: the galvanic compatibility of graphite composites and structural metals; electrochemical investigations; mechanically fastened joints; adhesively bonded joints; and moisture permeation in epoxy graphite composites.

76-08006 Naval Intelligence Support Center, Washington, D.C. Translation Div.

CORROSION AND PROTECTION OF SEAGOING SHIPS

E. V. Iskra, V. A. Klimova, and Yu. L. Kuzmin Sep. 1974 13 p
Transl. into ENGLISH from Mono. Korroziya i Zashchita Morskikh Sudov (Leningrad), 1973 p 93-102, 141-142
(AD-787290; NISC-Trans-3587)

This paper describes the corrosion resistance of Al-Mg and Al-Mg-Zn alloys in ships. Comparisons are made with steel hulls. Electrochemistry of corrosion is discussed.

76-08007 Air Force Inst. of Tech., Wright-Patterson AFB, Ohio. School of Engineering.

THE GALVANIC CORROSION OF GRAPHITE EPOXY COMPOSITE MATERIALS COUPLED WITH ALLOYS M.S. Thesis

Bennie A. Miller, Jr. Dec. 1975 99 p
(AD-A019322; GAE/MC/75D-8)

A controlled laboratory study was made of the galvanic corrosion that occurs when graphite-epoxy composite material (GECM) is coupled with various alloys in neutral 3.5% aqueous NaCl at room temperature. These tests simulated GECM/alloy joints that occur in aerospace applications. Previous work has shown that GECM acts as an extremely noble metal when coupled with a limited number of alloy types such as aluminum and titanium. This study extends this research by considering more alloy types, namely, steels, stainless steels, nickel base, copper, as well as aluminum and titanium. Four types of GECM were used along with pure graphite. Twenty-three alloys were tested for compatibility with GECM. Electrochemical test methods included potential measurements and galvanic current measurements. Galvanic current was measured by the use of a potentiostat modified to operate as a zero-resistance ammeter. Weight-loss tests were also conducted.

09

EXFOLIATION

N75-19434# Naval Ship Research and Development Center, Annapolis, Md.
CORROSION OF ALUMINUM ALLOYS IN EXFOLIATION-RESISTANT TEMPERS EXPOSED TO MARINE ENVIRONMENTS FOR TWO YEARS Research and Development Report
Ernest J. Czyryca and Harvey P. Hack Nov. 1974 23 p refs (SF54541)
(AD-A002234; NSRDC-4432) Avail: NTIS CSCL 11/6

The corrosion behavior of 5086, 5083, and 5456 aluminum alloys in H116 and H117 tempers was evaluated after 2 years of exposure to three marine environments; namely, fully submerged in sea water, splash and spray zone, and marine atmosphere. The alloys displayed good corrosion resistance with no exfoliation or pitting observed. Panels of the same alloys in a sensitized condition exposed to the same environments showed some pitting and edge attack but did not indicate a long-term corrosion problem. GRA

N76-18275# Air Force Materials Lab., Wright-Patterson AFB, Ohio
EFFECTS OF PURITY AND PROCESSING ON THE EXFOLIATION CORROSION BEHAVIOR OF 7X75 ALUMINUM PLATE Final Report, Mar. 1974 - Jan. 1975
Peter J. Blau Jul. 1975 22 p refs
(AF Proj. 7351)
(AD-A015728; AFML-TR-75-43) Avail: NTIS CSCL 13/8

The effect of varying iron and silicon content on the exfoliation corrosion behavior of two 7x75 type wrought aluminum alloys was investigated using the ASTM EXCO test. One series of alloy plates (5/8 inch thick) was basically the composition of 7475 with total iron and silicon varying in five steps between 0.03 and 0.31 weight percent. The other series contained Zr in place of Cr in the basic composition, and had a comparable variation in iron and silicon content. Each of the two series was processed both in the standard T651 temper and by a thermomechanical process (TMP). Twenty different combinations of composition and processing were studied this way. Test results showed that, in general, the variation in iron and silicon content had no significant effect on exfoliation resistance in either temper or alloy series. Corrosive attack on the TMP coupons was more uniform than on the T651 coupons. Long subsurface cracks were observed in the T651 coupons. Machined sides of the TMP coupons showed almost no attack, while those of the T651 coupons pitted. The depth of attack was about 1.5 times greater on the rolled surfaces of T651 coupons compared to TMP coupons. End-grain attack depth of T651 coupon sides was three times that of TMP coupon sides. Author (GRA)

10

LOCALIZED CORROSION

N74-13268# National Bureau of Standards, Washington, D.C. Inst. for Materials Research.
THE ROLE OF PASSIVE FILM GROWTH KINETICS AND PROPERTIES IN STRESS CORROSION AND CREVICE CORROSION SUSCEPTIBILITY **Technical Summary Report**
J. Kruger and J. R. Ambrose Jul. 1973 76 p refs
(Contract NAonr-18-69; NR Proj. 036-082)
(AD-767326; NBSIR-73-244; TSR-4) Avail: NTIS CSCL 11/6

The early stages of crevice corrosion of AISI 304 stainless steel in 1.0N NaCl solution have been detected using the ellipsometer to measure changes in optical properties occurring within the crevice between a polished metal surface and a glass plate. Changes in the ellipsometer parameters begin almost immediately upon creation of the crevice and can be interpreted as resulting from a build-up of soluble species within the crevice solution, followed by an overall thinning of the protective film and general corrosion attack. Such optical changes could not be reproduced by deoxygenation of the bulk solution without the presence of a crevice nor were they observed during experiments using a Ti-8Al-1Mo-1V alloy, which is not susceptible to crevice corrosion in the 1.0N NaCl at room temperature. Author (GRA)

N75-31262# Illinois Univ., Urbana. Dept. of Metallurgy and Mining Engineering.
FILM BREAKDOWN AND PITTING ***Final Report, 1 Sep. 1971 - 31 Dec. 1974***
M. Metzger 21 Apr. 1975 7 p refs
(Grant DA-ARO(D)-31-124-72-G28; DA Proj. 2O0-61102-B-32D)
(AD-A009788; ARO-5063.10-MC) Avail: NTIS CSCL 11/6

Aluminum was studied in sulfuric acid, with chloride to 0.1M, by electron microscopy, polarization and gravimetric methods. Film breakdown and transient pitting occurred in the absence of chloride. Chloride was not found to alter the film; its role was to stabilize pit embryo growth. Stable pit nucleation was conceived as requiring a pit embryo persistent enough to produce sufficient chloride enrichment within the pit. The observed absence of a sharp potential threshold for pit nucleation at low chloride levels was consistent with these views. GRA

N76-13279# Flow Research, Inc., Kent, Wash.
FUNDAMENTAL INVESTIGATION OF PITTING CORROSION IN STRUCTURAL METALS Final Report
Theodore R. Beck Jul. 1975 17 p refs
(Contract N00014-74-C-0227)
(AD-A012870) Avail: NTIS CSCL 07/4

Studies were made with an artificial pit in the side of a flow channel to obtain quantitative data on hydrodynamic effects on pitting rate. Experiments were conducted under potentiostatic conditions with titanium, aluminum and iron in chloride, bromide and iodide solutions. Two modes of pitting were observed; a high current density limited only by ohmic resistance in solution and a lower current density limited by mass transport of some species. The mass transport limited mode was observed in addition to the ohmic mode for titanium in bromide and iodide and for iron in chloride solution. GRA

A73-34671 **Filiform corrosion associated with commonly applied aircraft metal pretreatments and finishes.** M. Gann (Cessna Aircraft Co., Wichita, Kan.). *Society of Automotive Engineers, Business Aircraft Meeting, Wichita, Kan., Apr. 3-6, 1973, Paper 730311.* 10 p. Members, $1.25; nonmembers, $2.00.

A73-43521 * **Pitting of titanium. I - Titanium-foil experiments. II - One-dimensional pit experiments.** T. R. Beck (Flow Research, Inc., Kent, Wash.). *Electrochemical Society, Journal,* vol. 120, Oct. 1973, p. 1310-1324. 31 refs. Contracts No. NASw-2245; No. NAS7-489; No. F44620-72-C-0070.

Pitting experiments were conducted with strips of titanium foil in beakers containing chloride, bromide, or iodide solutions. The potentials were determined in reference to the saturated calomel electrode. Corrosion occurred at the edge of a foil specimen when it was maintained at a potential between the steady-state pitting potential of about 0.9 V and a potential of about 1.4 V in neutral bromide solution. A model is discussed to account for the complex relationships observed in the experiments. Conclusions based on experiments conducted with one-dimensional pits at the ends of insulated titanium pencils in the anode-facing-up position are also presented. G.R.

A74-32672 # **Airframe maintenance and corrosion protection.** H. Tyrer (British Aircraft Corp., Ltd., Weybridge, Surrey, England). *Tech Air,* vol. 30, June 1974, p. 5, 6.

Transgranular and intergranular corrosion in aircraft structures give rise to visible deposits that can be detected by a trained observer prior to cleaning. Scraping, drying, and treatment with a good de-watering fluid will provide temporary protection until the regular maintenance period, when the area can be thoroughly renovated and recoated. Specific protective procedures and agents are described, and the general symptoms and causes of corrosion are discussed. J.K.K.

A74-35279 **Recent Air Force electronic systems corrosion problems.** F. H. Meyer, Jr. (USAF, Materials Laboratory, Wright-Patterson AFB, Ohio). *National Association of Corrosion Engineers, International Corrosion Forum Devoted Exclusively to the Protection and Performance of Materials, Chicago, Ill., Mar. 4-8, 1974, Paper 24.* 6 p. $1.50.

Review of some of the corrosion problems encountered in Air Force electronic systems, and discussion of the corrosion prevention requirements these problems suggest. The most common cause of corrosion in electronic equipment is shown to be water condensation on components not specifically selected or protected. Dissimilar metals in contact and inadequate removal of solder flux are among the other corrosion causes discussed. M.V.E.

A74-44069 # **Corrosion on aircraft - Evaluation, examination, and elimination. II (Korrosion an Luftfahrzeugen - Ihre Beurteilung, Prüfung und Behebung. II).** H. Ebert (Staatliche Luftfahrtinspektion, Berlin, East Germany), R. Hermann, and A. Römer (VEB Kombinat Spezialtechnik, Dresden, East Germany). *Technisch-ökonomische Informationen der zivilen Luftfahrt,* vol. 10, no. 4, 1974, p. 206-214. 8 refs. In German.

The occurrence of corrosion on the various sections and components of an aircraft is considered. Visual inspection regarding corrosion attack is supplemented by measurements of corrosion depth. Approaches for periodic corrosion control measures are discussed together with the determination of the causes of corrosion and decisions regarding the remaining operational life of components before corrective action must be taken. Procedures are described for the elimination of corrosion damage in the case of aluminum, magnesium, and iron materials. G.R.

N75-76539 Air Force Systems Command, Wright-Patterson AFB, Ohio. Foreign Technology Div.
INVESTIGATION AND EXPERIMENTATION IN THE USE OF TITANIUM AS A STRUCTURAL MATERIAL FOR HYDROMETALLURGICAL APPARATUS
V. B. Zhilkin Oct. 1973 8 p Transl. into ENGLISH from Mono. Novyi Konstruktsionny Material, Titan (USSR), 1972 p 200-202
(FTD Proj. 60107; FTD Proj. T74-01-10)
(AD-770864; FTD-HT-23-160-74)

Under conditions of a nickel electrolysis plant, all titanium samples tested were found to be in the stable, passive state and are completely stable, and showed no disposition to intercrystalline corrosion. The strength of weld seams is equivalent to the strength of the base metal. Technological working (casting, hot deformation, mechanical treatment) does not reduce the corrosion resistance of titanium alloys under test conditions.

N75-78270 Army Mobility Equipment Research and Development Center, Fort Belvoir, Va.
HEAT EXCHANGER CORROSION TESTS, PHASE 2

Oscar Oldberg Jul 1973 10 p
(AD-771918)

The results of the test program indicate that all-aluminum condensers may be substituted for the copper tube-aluminum fin construction currently used in military ECU's (Environmental Control Units) in the interest of cost savings. However, care should be exercised at the tube joint with any dissimilar metals, which should be protected with a moisture proof external seal.

N75-78370 Air Force Systems Command, Wright-Patterson AFB, Ohio. Foreign Technology Div.
THE MECHANISM OF TITANIUM PASSIVATION IN SULFURIC AND HYDROCHLORIC ACID SOLUTIONS
A. P. Bryinza and V. P. Fedash Nov. 1973 12 p Transl. into ENGLISH from Mono. Novyi Konstruktsionny Material-Titan (USSR), 1972 p 179-183
(FTD Proj. 60107; FTD Proj. T74-01-10)
(AD-769563; FTD-HT-23-154-74)

One of the fundamental problems involved in the study of the passivation of metals is an explanation of the nature and means of the phenomenon's initiation. In an attempt to explain the mechanism of titanium (VT1-1 brand) passivation, the article studies its electro-chemical behavior in 5 and 10 N solutions of sulfuric and hydrochloric acid using the following methods: relaxation of polarization, stationary and nonstationary curves, potential drop curves, and the alternating current method. This article also measures the amount of electricity expended in a given period of time on anode passivation of titanium and on the reduction of oxide films which form at various passivation potentials.

N75-70423 Bendix Field Engineering Corp., Columbia, Md.
AVIONICS CORROSION CONTROL STUDY Final Report, Oct. 1973 - Jan. 1974
Jan. 1974 55 p
(Contract N62269-74-C-0168)
(AD-A011177)

The objectives of this report are to offer the Navy a limited study of some of the problems and possible solutions associated with avionics corrosion control that could be the basis of a manual devoted to that subject. The research methods employed sought information from two sources: (1) published material from secondary sources to take advantage of what is already known and documented in the literature, and (2) primary sources derived from activities and experiences within the Bendix Field Engineering Corporation. The conclusion to be drawn is that the essential difference between corrosion problems in large structures and corrosion attacking avionic equipment is that minute corrosion products that could degrade or disable complicated avionic equipment would go unnoticed on large mechanical structures. The results of the investigation correlate positively with previous Bendix work in corrosion phenomena and control.

76-10001 * Flow Research, Inc., Kent, Wash.
PITTING OF TITANIUM. 1: TITANIUM-FOIL EXPERIMENTS
T. R. Beck May 1973 8 p Pub. in J. Electrochem. Soc., v. 120, no. 10, Oct. 1973 p 1310-1316 Revised Prepared in cooperation with Boeing Scientific Research Labs.
(Contracts NAS7-489; F44620-72-C-0070)
(AD-772374; AFOSR-73-2187TR)

Experiments were conducted in which pitting occurred at the edges and on the circumference of holes in titanium foil in chloride, bromide, and iodide solutions under potentiostatic conditions. Valence of dissolution was approximately 4, the effect of potential, temperature, concentration, pH, and solution flow on current density and pitting potential was determined. Very complex behavior not fitting a single kinetic, mass transport, or ohmic limitation was observed. A model combining a salt film on the metal surface with events in the electrolyte diffusion layer qualitatively fits the data. Author

76-10002 Army Electronics Command, Fort Monmouth, N.J.
CONDUCTIVE, LUSTRELESS, ABRASION RESISTANT, ELECTRODEPOSITED COATINGS
Aubrey J. Raffalovich Sep. 1974 22 p
(DA Proj. 1S7-62705-AH-94)
(AD-786498; ECOM-4257)

The report describes a process for electrodepositing lustreless conductive coatings on various alloys of aluminum, steel and copper. Initial work was plating over steel. The emphasis of the internal study was the plating of aluminum alloys. Alloys of aluminum are difficult to plate because of the ever present film of insulating oxide. Special techniques are required to electroplate any metal over aluminum. Aluminum alloys 1100, 6061, 40E, 356 and 380 were successfully plated and met the specific requirements for color, gloss, abrasion resistance, corrosion resistance, adhesion-flexibility and contact resistance. Alloy 2024 was rated fair with regard to adhesion of the plating. Alloy 5052 presented a problem with regard to obtaining adequate nickel adhesion to the alloy. Author

76-10003 Aerojet Liquid Rocket Co., Sacramento, Calif.
STORABILITY INVESTIGATIONS OF WATER LONG-TERM STORAGE EVALUATION Annual Report
E. M. VanderWall and G. R. Janser Dec. 1974 65 p
(Contract F04611-72-C-0062; AF Proj. 3059)
(AD-A004462; AFRPL-TR-74-76; AR-1)

The objective of this program is to gather data that will permit the Air Force to assess the long term storage characteristics of water, particularly with regard to formation of particulate matter, so that the feasibility of long-term storage of water for use as a transpiration coolant can be determined. Five metallic materials of construction are included in the program: 304 stainless steel, A-286 (aged) steel, 17-4 (aged) stainless steel, Inconel 718 (aged), and 6Al-4V titanium (STA). Two types of water are used in the program: oxygen-saturated, deionized, filtered, and oxygen-free, deionized, filtered. Evaluation of water and containers stored for six-months and twelve-months has been completed. The data show that both oxygen-saturated and oxygen-free water can be stored in appropriate metal containers for the selected time periods without detrimental particulate matter formation or significant changes in the quality of the water. It is in excellent condition for transpiration coolant purposes.

76-10004 Illinois Univ., Urbana. Dept. of Metallurgy and Mining Engineering.
BREAKDOWN OF FILMS AND INITIATION OF PITS ON ALUMINUM DURING ANODIZING
J. Zahavi and M. Metzger 1974 10 p Pub. in Localized Corrosion, NACE-3, 1974 p 547-555
(Grant DAHC04-74-G-0016)
(AD-A005258; ARO-5063.4-MC)

The present work sought to gain insight into the nature of the initial film failure leading to pitting of aluminum through electron microscope studies of the microtopography of the film and substrate. Author

76-10005 Hughes Helicopters, Culver City, Calif.
RELATIONSHIP BETWEEN INTERGRANULAR CORROSION SUSCEPTIBILITY AND STRESS CORROSION RESISTANCE OF ALUMINUM ALLOY FORGINGS Final Report, Jul. 1974 - Sep. 1975
J. C. French, W. W. Jarrett, E. Y. Tsao, and J. M. Thorp Sep. 1975 100 p
(Contract DAAJ01-74-C-0590)
(AD-A017751; USAAVSCOM-TR-75-45)

The objectives of the program were: (1) to establish an empirical correlation between severity of intergranular corrosion and time to failure caused by stress corrosion, and (2) to establish a maximum level of severity for intergranular corrosion in aluminum forgings that may be used as an acceptance criterion.

76-10006 Naval Surface Weapons Center, White Oak, Md.
CORROSION AND FOULING STUDY Final Report
John H. S. McMann Jul. 1975 43 p
(AD-A020071; NSWC/WOL/TR-75-113)

This report investigates the anticorrosion and antifouling properties of 24 commercially available coatings applied to 6061-T6 aluminum and submerged in seawater for a period of up to 18 months. Described in the report are the test panels and their coatings, the test conditions and following test results: quantity and type of fouling, pitting, erosion and galavanic corrosion and coating adherence, smoothness and hardness.

11

COATINGS, SURFACE FINISH AND PLATING

N73-22514# Pennsylvania State Univ., University Park. Materials Research Lab.
PREPARATION OF METAL-OXIDE-HYDROXIDE PROTECTIVE LAYERS UNDER CONTROLLED pO2-pH2O-T CONDITIONS Final Report, 1 Mar. 1967 - 31 Mar. 1972
Frank Dachille, E. W. White, and Rustum Roy 25 Jan. 1973 16 p refs
(Contract N00014-67-A-0385-0002; NR Proj. 032-502)
(AD-755729) Avail: NTIS CSCL 11/6

The report briefly summarizes research on work concerned with the preparation of oxidation films on metals under various pO2, pH2O, and temperature conditions and the characterization of these films. The thrust of the research was to seek out conditions which would lead to the formation of corrosion resistant oxide or hydroxide films. The metals considered for study were narrowed down to aluminum and iron, along with titanium, nickel and chromium. The principal method for characterization of the corrosion films are soft X-ray spectroscopy, and X-ray diffraction. GRA

N73-31544# Air Force Systems Command, Wright-Patterson AFB, Ohio. Foreign Technology Div.
ELECTROLYTIC AND CERTAIN OTHER METHODS FOR APPLYING TITANIUM COATING
G. A. Kolobov 29 Jun. 1973 18 p refs Transl. into ENGLISH from Sb. Tr., Met. Khim. Titana (USSR), v. 5, 1970 p 66-75
(AD-764318; FTD-HT-23-450-73) Avail: NTIS CSCL 11/3

The Russian report presents a brief discussion of methods for applying protective titanium coatings. GRA

N74-10493# Defense Documentation Center, Alexandria, Va.
ELECTROPLATING Bibliography Report, Dec. 1955 - May 1972
Mar. 1973 152 p refs
(AD-756800; DDC-TAS-73-16) Avail: NTIS CSCL 11/3

The bibliography contains unclassified and unlimited references to reports on the process of coating metals and composites by the Electroplating technique. Author (GRA)

N74-16162# Defense Documentation Center, Alexandria, Va.
TECHNIQUES IN PLATING Report Bibliography, Mar. 1957 - Jun. 1973
Nov. 1973 482 p refs
(AD-769400; DDC-TAS-73-64) Avail: NTIS CSCL 13/8

The bibliography is a collection of references relating to techniques in plating and coating. The references deal primarily with types of plating, materials used for plating, and plated surface. Also, the mechanical properties of deposited protective coatings are discussed. Corporate Author-Monitoring Agency, Subject, Title and Personal Author Indexes are included. GRA

N74-17281# IIT Research Inst., Chicago, Ill.
DEVELOPMENT OF CORROSION INHIBITORS AND ADHESION PROMOTERS Final Report, 4 Apr. 1972 - 6 Jul. 1973
K. S. Rajan and P. K. Ase 25 Jul. 1973 52 p refs
(Contract N00019-72-C-0446)
(AD-770627; IITRI-C6252-7) Avail: NTIS CSCL 11/6

The treatment of aluminum alloys by (1) polyaminocarboxylic acids, (2) hydroxycarboxylic acids, (3) authraquinones, (4) diazo compounds and, (5) phthalocyanine have all been found to result in the deposition of a multimolecular layer of the individual ligands on the oxidic surface of the metal. Considerably improved paint adherence numbers were shown by the chelate-treated coupons over those of the conventional CHEMRITE-treated ones. However, in the salt splash tests, the unpainted coupons which had been chelate-treated showed decidedly more rapid corrosion attack than the CHEMRITE-treated ones. This could be due to the ease of washability of the surface-bound ligand. A pretreatment of the aluminum coupons with 0.5% CHEMRITE followed by surface chelation by alizarin and its analogs and phthalocyanine has shown not only considerably improved paint-adherence but also a satisfactory corrosion protection in comparison with the conventional CHEMRITE-treatment. GRA

N74-32005# Battelle Columbus Labs., Ohio. Metals and Ceramics Information Center.
PROCEEDINGS OF THE 1973 SYMPOSIUM ON ELECTRO-DEPOSITED METALS FOR SELECTED APPLICATIONS
William H. Safranek and Ralph G. Dermott May 1974 129 p refs Symp. held on 4-15 Nov. 1973
(Contract DSA900-74-C-0616)
(AD-779152; MICI-74-17) Avail: NTIS HC $12.25; MF $12.25 CSCL 11/3

A total of 12 papers were presented at the symposium. Important subjects discussed included, reliability of electrodeposits on aluminum electrical connectors, aluminum-manganese alloy deposits, nickel foil produced from sulfamate solutions at high deposition rates, fatigue life of nickel-plated hardened steel, nickel-cobalt alloys for electrojoining, electroless nickel deposits, oxide coatings, high-rate (over one mil per minute) deposits. In addition nondestructive testing was discussed and properties of vacuum-deposited and electrodeposited coatings were compared. (Modified author abstract) GRA

N75-30319# Army Foreign Science and Technology Center, Charlottesville, Va.
THE EFFECT OF NAIRIT COATINGS ON CYCLIC STRENGTH OF SAMPLES AND PARTS SUBJECT TO FRETTING CORROSION
V. S. Ivanova and M. G. Veitsman 11 Jul. 1974 10 p refs Transl. into ENGLISH from Ustalost Metal. i Splavov, M. (USSR), 1941 p 103-108
(AD-A006098; FSTC-HT-23-0545-74) Avail: NTIS CSCL 11/3

Coating the mating surfaces of metal parts with Nairit is a new and promising method of preventing fretting corrosion. Nairit is a variety of synthetic rubber which can be applied by simple industrial processes. Comparative tests made on Nairit coatings showed them to be superior to any other protective method used up until now. The article includes results and methods of testing for steel and aluminum parts. By preventing fretting corrosion caused by friction, cyclic strength of components is greatly increased. GRA

N76-12176# Naval Air Development Center, Warminster, Pa. Air Vehicle Technology Dept.
CHROMATE CONVERSION COATING OF ALUMINUM ALLOYS
S. J. Ketcham and S. R. Brown 10 Jul. 1975 19 p refs
(AD-A012802; NADC-75125-30) Avail: NTIS CSCL 13/8

This report describes the variables inherent in the processing of aluminum alloys with chromate conversion coatings. These include cleaning, deoxidizing, chromating, rinsing, as well as metal source and heat treatment effects. An optimum process for chromating aluminum alloys for military usage is outlined. Author (GRA)

N76-12177# Naval Air Development Center, Warminster, Pa. Air Vehicle Technology Dept.
AERONAUTICAL ANALYTICAL REWORK PROGRAM: THIXOTROPIC CHEMICAL CONVERSION COATING FOR THE CORROSION PROTECTION OF AIRCRAFT ALUMINUM SURFACES Final Report
P. N. Bellavin 6 Jun. 1975 25 p
(AD-A012345; NADC-75024-30) Avail: NTIS CSCL 11/3

This report covers processes for application and the use of a sprayable/brushable thixotropic, chemical conversion coating for the corrosion protection of aircraft skin surfaces and components. Results of field evaluations, specification performance and formulations are given. Current application problems encountered during rework operation in the control of rapid run-off from vertical and curved aircraft surfaces are discussed. GRA

A73-23522 # **Resistant finishes.** J. B. G. Lewin. *Aircraft Engineering*, vol. 45, Feb. 1973, p. 11, 12.

Aircraft surface primers and finishes designed to withstand

severe environmental conditions are described in terms of composition, pretreatment, and application factors governing flexibility, adhesion, water resistance, hardness, and chemical stability. The properties of amine and polyamide cured epoxy primers are summarized along with important features of acrylic, epoxy, and polyurethane finishes. T.M.

A73-29316 **Compatible coatings for corrosion resistant aerospace fasteners.** E. Taylor (Standard Pressed Steel Co., Jenkintown, Pa.). *National Association of Corrosion Engineers, International Corrosion Forum Devoted Exclusively to the Protection and Performance of Materials, Anaheim, Calif., Mar. 19-23, 1973, Paper 116.* 8 p. 11 refs. $1.50.

There is some hesitation in specifying a coating for a material which is resistant to corrosion, even though the degree of resistance varies widely with alloys labelled 'corrosion resistant.' Coatings for fasteners have generally been sacrificial in nature so that the base metal is prevented from corroding or breaking. Magnesium, the metal most likely to protect aluminum structure, is uneconomical to produce as a fastener coating, is very reactive, and is rapidly consumed in corrosive environments. Laboratory evidence overwhelmingly reveals the desirability of corrosion-resistant high strength fastening alloys as a replacement for the corrosion-prone plated alloy steels. F.R.L.

A74-11588 **A corrosion inhibiting coating for structural airframe fasteners.** F. L. Gill (Hi-Shear Corp., Reading, Pa.). *Society of Automotive Engineers, National Aerospace Engineering and Manufacturing Meeting, Los Angeles, Calif., Oct. 16-18, 1973, Paper 730902.* 8 p. 5 refs. Members, $1.25; nonmembers, $2.00.

Corrosion problems associated with using titanium fasteners to assemble aluminum airframe structures are reviewed. Data are presented describing the effectiveness of metallic platings and an aluminum filled organic based coating on fasteners to render the titanium-aluminum electrochemical couple inoperative. The aluminum enriched organic coating known as Hi-Kote 1 is shown to be more effective in minimizing corrosive attack on aluminum airframe structure in both saline and acidic environments. The effectiveness of Hi-Kote 1 in corrosion-fatigue tests of fastened aluminum structure is also reported. (Author)

A74-16592 Fretting resistant coatings for titanium alloys. D. J. Padberg (McDonnell Aircraft Co., St. Louis, Mo.). In: Titanium science and technology; Proceedings of the Second International Conference, Cambridge, Mass., May 2-5, 1972. Volume 4. New York, Plenum Press, 1973, p. 2475-2486. Contract No. F33615-70-C-1538.

Investigation of the safe use of fretting-resistant coatings for the prevention of fretting-induced fatigue failures in aircraft components made of titanium alloys. The specific study goals explored and results presented pertain to: (1) the determination of fretting conditions prerequisite to fatigue life shortening in a titanium airframe joint; (2) evaluation and selection of potential fretting-resistant coatings that would not impair the properties of the basis metal; and (3) test of promising fretting-resistant coatings on experimental test elements using the critical fretting conditions determined under (1). M.V.E.

A74-44530 # **Minimizing hydrogen pick-up during electroplating of high-strength steels.** A. G. Sussex (Australian Defence Scientific Service, Defence Standards Laboratories, Melbourne, Australia). In: Effects of chemical environment on fracture processes; Proceedings of the Third Tewksbury Symposium, Melbourne, Australia, June 4-6, 1974.
Melbourne, University of Melbourne, 1974, p. 98-108. 23 refs.

The recent history of the problem hydrogen pickup during electroplating, as solved to date by the aircraft industry, is briefly outlined as a guide to potential users of high- and ultrahigh-strength steels. The cracking of high-strength steel promoted by hydrogen embrittlement is a special case in fracture mechanics and some metallurgical (solid state) and electrochemical (solid-liquid interface) aspects of minimizing embrittlement are discussed. The basis of some preferred techniques is briefly reviewed. (Author)

A75-32680 # **Ion vapor deposited aluminum improves structure durability.** E. R. Fannin and K. E. Steube (McDonnell Aircraft Co., St. Louis, Mo.). *AIAA, ASME, and SAE, Structures, Structural Dynamics, and Materials Conference, 16th, Denver, Colo., May 27-29, 1975, AIAA Paper 75-807.* 6 p. 5 refs.

Two fairly recent changes in airframe structure have had an impact on the corrosion protective coatings used. First, the fatigue improvements resulting from the use of interference fit fasteners can be greatly reduced if anodic coatings are applied to the aluminum structure. The second change involves the increased utilization of titanium structure which places a restriction on the use of cadmium plating because of potential solid metal embrittlement. Data is presented to show that ion vapor deposited aluminum coatings can be substituted for both of the above coatings without these undesirable effects. Additional performance comparisons of the aluminum coating will also be described. (Author)

12

POWER GENERATION, FUELS AND COMBUSTION

N75-18228# AiResearch Mfg. Co., Torrance, Calif.
CATALYTIC REACTOR FOR INERTING OF AIRCRAFT FUEL TANKS Final Report, Jun. 1971 - Jun. 1974
George H. McDonald and J. Rousseau Jun. 1974 117 p refs
(Contract F33615-71-C-1901; AF Proj. 3048)
(AD-A000939; Rept-74-10294; AFAPL-TR-74-49) Avail: NTIS CSCL 01/3

The program, Catalytic Reactor for Inerting of Aircraft Fuel Tanks, was concerned with the development of a prototype catalytic reactor for the generation of inert gases through jet fuel combustion in engine bleed air. Successful operation of a flight-configured unit was achieved at very high effectiveness. Inert gas oxygen concentrations below 1 percent were achieved repeatedly. Design data were generated related to reactor performance under various operating conditions and also related to thermal and mechanical design of the unit. Corrosion testing of aircraft fuel tank construction materials including metals, coatings, and sealants was conducted. These materials were evaluated in terms of resistance to corrosion by SO2 formed in the fuel oxidation reactor. A complete fuel tank inerting system was synthesized. GRA

N75-24929# Bell Aerosystems Co., Buffalo, N.Y.
ANALYSIS OF THE LIQUID ROCKET TANKAGE Final Report
John Salvaggi, H. G. Kammerer, and E. J. King Apr. 1975 260 p refs
(Contract F04611-74-C-0007)
(AD-A008535; AFRPL-TR-74-82) Avail: NTIS CSCL 11/6

The objective of this program was the assessment of storage container compatibility with N2O4, and ClF5, for periods of time up to and including 6 years of pressurized exposure. Tankage materials were aluminum alloys 2021, 2014, 2024, 2219, 6061, 7039, X7007, and 5456, as well as Arde 301 stainless steel, A-286 and Inconel 718. Two types of N2O4 were evaluated for compatibility, namely oxygenated and unoxygenated. The evaluation of the storage containers revealed that the major source of degradation was external. The primary cause of corrosion was the dilute acid, high humidity storage area environment. Internal corrosion observed in a very limited number of containers was attributable to a lack of thorough rinsing after exposure. The majority of internal surfaces showed little or no degradation from either oxidizer. GRA

76-12001 Air Force Systems Command, Wright-Patterson AFB, Ohio. Foreign Technology Div.
FUELS AND LUBRICANTS FOR AIRCRAFT
M. E. Reznikov Feb. 1975 339 p Transl. into ENGLISH from Mono. Topliva i Smaz. Mater. Dlya Letatelnykh Apparatov (Moscow), 1973 p 1-231
(AD-A018261; FTD-HC-23-2134-74)

Contents: general characteristics of aircraft fuels; brief data on the production of fuels--petroleum the basic raw material in fuel production; fuels for air breathing jet engines; aviation gasolines--piston engines and fuel requirements; rocket propellants; lubricants and technical fluids; production of synthetic oils and liquids; oils for aircraft engines; transmission oils; and greases.

13

MATERIALS SELECTION, TESTING, AND EVALUATION

N73-25622# Air Force Systems Command, Wright-Patterson AFB, Ohio. Foreign Technology Div.
RESEARCH OF PROPERTIES OF ALLOY TB2 TITANIUM
O. M. Shapovalova, Y. K. Molchahova, and L. K. Mineyeva 13 Apr. 1973 15 p Transl. into ENGLISH from Sb. Tr. Met. Khim. Titana (USSR), no. 6, 1970 p 117-122
(AD-759621; FTD-HT-23-1713-72) Avail: NTIS CSCL 11/6
Experiments determined that the titanium alloy TB2 can be used not only as a high-strength and heat-resistant alloy, but at the same time as a corrosion-resistant alloy in various hostile media. GRA

N73-25837# Air Force Systems Command, Wright-Patterson AFB, Ohio. Foreign Technology Div.
THE MANUFACTURE OF THE BASIC PARTS OF AIRCRAFT ENGINES
M. I. Evstigneev and I. A. Morozov 31 Jan. 1973 663 p refs Transl. into ENGLISH of the mono. "Izogotovlenie Osnovnykh Detalei Aviatvigatelei" Moscow, Izd-vo Mashinostroyeniye, 1972 p 1-478
(FTD Proj. 60108; FTD Proj. T72-01-40)
(AD-759577; FTD-MT-24-1460-72) Avail: NTIS CSCL 21/5
In the book, which is an educational aid for students of aviation higher educational institutes and schools, are discussed the technological processes of manufacture of the critical parts of engines of flight vehicles. Their structural features, technical specifications for manufacture and materials, the structure of technological processes, the methods of carrying out basic operations, methods and means of control are examined. Information is given on the technology of manufacture of parts from plastics and refractory materials. Author (GRA)

N73-26492# Lockheed Missiles and Space Co., Sunnyvale, Calif.
***EVALUATION OF NITINOL FITTINGS FOR JOINING* TITANIUM PIPING FOR SHIPBOARD APPLICATIONS Final Report, 9 Mar. 1972 - 8 Apr. 1973**
Marsh K. Eckhardt 30 Apr. 1973 60 p refs
(Contract N00024-72-C-5336)
(AD-760322; LMSC-D350045) Avail: NTIS CSCL 13/5
Basic tests were made of Cryofit heat shrinkable fittings used with C.P. titanium and Ti-3Al-2.5V tube. Tests included flexural fatigue, tensile, burst, torsion and crevice corrosion. Tube sizes of 1.90 in. and 4.0 in. diameter were tested. There were no fitting failures, and flexural life degradation by the fitting was under 10% with Ti-3Al-2.5V tube and less than 20% with C.P. grade 3 tube. The fitting designs were based on 3000 psi aircraft hydraulic system requirements and it is believed even better results might be obtained with designs modified to suit lower pressure Navy systems. The Cryofit fittings can be used with Ti-3Al-2.5V and commercially pure tubing up to 4 in. diameter except in systems of safety significance, i.e., per MIL-STD-882, Class IV or Class III. With further in-depth testing, they could probably be used in any system as original installation or retrofit. Author (GRA)

N73-27464# Westinghouse Electric Corp., Pittsburgh, Pa. Astronuclear Lab.
MODIFICATION AND CONTROL OF OXIDE STRUCTURES ON METALS AND ALLOYS, PHASE 3 Final Report, 20 Dec. 1971 - 20 Jan. 1973
Robert C. Svedberg Feb. 1973 199 p refs
(Contract N00019-72-C-0132)
(AD-761215; WANL-M-FR-73-003) Avail: NTIS CSCL 11/6
The rutile structure family for oxide compounds of the type Nb(B)O4 where B = Cr, Al, or Fe have been identified as being the primary oxide phase in the scales formed on oxidation resistant Nb intermetallic compounds and Nb-Ti-Cr-Al, Nb-Fe-Al, Nb-Cr-Al-Co, and Nb-Cr-Al-Ni alloys. Along with this oxide, small amounts of either (B)2O3 where B = Cr, Al, or Fe or a CoAl2O4 spinel in cobalt containing alloys were detected. Oxygen transport rates through Nb2O3-Cr2O3, Nb2O5-TiO2, Nb2O5-ZrO2, and Nb2O5-Al2O3 were also determined using thermogravimetric techniques. Of the oxide compounds evaluated, only oxygen transport through Nb2O5-Cr2O3 was slow enough to warrant its classification as a protective scale. In addition to oxidation rate data, metallographic studies and electron microprobe studies are reported for the Nb intermetallic compounds and alloys. Author

N73-28587# Battelle Columbus Labs., Ohio.
ENGINEERING DATA ON NEW AEROSPACE STRUCTURAL MATERIALS Final Summary Report, Apr. 1972 - Apr. 1973
Omar L. Deel, Paul E. Ruff, and H. Mindlin Jun. 1973 149 p
(Contract F33615-72-C-1280; AF Proj. 7381)
(AD-762305; AFML-TR-73-114) Avail: NTIS CSCL 11/6
The major objectives of the research program were to evaluate newly developed materials of interest to the Air Force for potential structural airframe usage, and to provide data sheet type presentations of engineering data for these materials. The effort covered in the report has concentrated on X2048-T851 plate, 7050-T73651 plate, 21-6-9 annealed sheet, Ti-8Mo-8V-2Fe-3Al STA sheet, Ti-6Al-2Zr-2Sn-2Mo-2Cr STA plate, and Ti-6Al-6V-2Sn STA isothermal die forgings. The properties investigated include tension, compression, shear, bend, impact, fracture toughness, fatigue, creep and stress-rupture, and stress corrosion at selected temperatures. Author (GRA)

N73-29930 *Aeronautical Systems Div., Wright-Patterson AFB, Ohio.*
ON FATIGUE ANALYSIS AND TESTING FOR THE DESIGN OF THE AIRFRAME
Walter J. Crichlow *In* AGARD Fatigue Life Prediction for Aircraft Struct. and Mater. May 1973 36 p refs

The experimental and analytical techniques for controlling time to fatigue crack initiation in design of aircraft structure are reviewed to define improvements that may be gained from available research knowledge. Discrepancies among simple theory, experiment, and service are being better explained by accountability for residual stress systems created by higher than average loading peaks recurring randomly throughout the service load spectrum. Analytical accounting for the generation, decay, and recreation of residual stress spectra is an essential adjunct to the experimental approach, for not all parts can be critically tested, and not all load spectra variations can be accommodated in test. Recent advances in residual stress analyses are reviewed. Failure theory, interaction matrix, chemical (corrosion), and mechanical (fretting) environmental aspects are explored. Variability of results are discussed in terms of design life reduction factors. Author

N73-31458# Naval Intelligence Support Center, Washington, D.C. Translation Div.
STATE OF THE ART OF ARGON-ARC WELDING TECHNOLOGY IN JOINING ALUMINUM AND ALUMINUM ALLOYS TO STEEL
G. A. Belchuk, V. R. Ryabov, and V. I. Yumatova 12 Jul. 1973 47 p Transl. into ENGLISH of the mono. "Sovremennoe Sostoyanie Tekhnologii Argono-Dugovoi Scarki Alyuminiya i Ego Splavov so Stalyu" Leningrad, 1967 p 11-27, 130-137, 163-173
(AD-763948; NISC-Trans-3453) Avail: NTIS CSCL 13/8
Topics included are the use of alloyed filler metal, special features of welding aluminum alloy to 18-8(1Kh18N9T) steel, corrosion resistance of welded aluminum-alloy and steel joints, some examples of industrial application of argon-arc welding technology in joining aluminum and aluminum alloy to steel, some fields of application of chromium-nickel austenitic steels, and properties of the most widely-used Fe-Cr-Ni-Mn and Fe-Cr-Mn steels. GRA

N74-10494# Denver Research Inst., Colo.
CENTER FOR HIGH ENERGY FORMING Semiannual Technical Report, 1 Jan. - 30 Jun. 1973
Henry E. Otto Jul. 1973 33 p refs
(Contract DAAG46-72-C-0130, ARPA Order 720)
(AD-766213; AMMRC-CTR-73-23; SATR-2) Avail: NTIS CSCL 13/8
The report summarizes work at the Center for High Energy

Forming include: A metallurgical investigation of explosion welded copper-nickel composites; Determination of the optimum parameters for explosion welding A515 steel; Analysis and design of an explosion cladding facility; Free forming steel domes with D/t ratios of 56 and greater; the mechanics of energy transfer from underwater explosions; The explosive free-forming of arbitrary shapes from thin metal sheets; Stress corrosion cracking behavior of explosively deformed austenitic stainless steel; Explosive thermomechanical processing of beta III Titanium alloy; Explosive compaction of nickel base superalloy powders; Engineering economics of the explosive forming manufacturing facilities. (Modified author abstract) GRA

N74-11843# Laboratorium fuer Betriebsfestigkeit, Darmstadt (West Germany).
REVIEW OF INVESTIGATIONS ON AERONAUTICAL FATIGUE IN THE FEDERAL REPUBLIC OF GERMANY, MAY 1969 - JUNE 1973
E. Gassner and O. Buxbaum Jun. 1973 140 p refs Presented at the 13th Conf. of the Intern. Comm. on Aeron. Fatigue, London, 1973
(LBF-S-108) Avail: NTIS HC $9.00

A review is presented of the work carried out in the field of fatigue of aircraft structures in Germany. Most of the subjects treated are fatigue test results from specimens and components including effects of surface treatment and corrosive environment. Other reports concern loads measured in service and their analysis. Investigations concerning cyclic stress-strain behavior as well as crack propagation, residual strength, and fracture toughness are also reported. ESRO

N74-13264# Rohr Corp., Chula Vista, Calif.
DEVELOPMENT OF A FILLER METAL AND JOINING PROCESS FOR TITANIUM-ALLOY HONEYCOMB PANELS Final Report, Jul. 1971 - May 1973
J. R. Woodward Wright-Patterson AFB, Ohio AFML Jul. 1973 144 p
(Contract F33615-71-C-1888; AF Proj. 7351)
(AD-767227; AFML-TR-73-125) Avail: NTIS CSCL 11/6

The second generation beta titanium alloys, Beta III, RMI 38-6-44 and TMCA 88-23, were furnished in foil and fabricated into honeycomb core. All three alloys responded well to the core manufacturing process. Thermal effect studies showed that all of the beta titanium alloys were relatively unaffected by high temperature, long time exposures when in foil form. Sheet forms resulted in grain growth under the same conditions. The Rohr Industries, Inc. proprietary LID(TM) bonding process showed the highest strength joints of all other systems tested. Sandwich panels made with the three beta titanium cores bonded to Ti 6Al 4V faces were measured in all sandwich test modes. The data were compared with sandwich structure made with the same joining system except with Ti 3Al 2.5V core. Results showed that significant strength improvements can be realized by using beta titanium core. Projections also show that material cost economies may be realized by using beta titanium core.
Author (GRA)

N74-17263# Brown Univ., Providence, R.I.
THERMOMECHANICAL PROCESSING BETA TITANIUM Final Report, 11 May 1972 - 10 Aug. 1973
Donald H. Avery and Ned W. Polan Sep. 1973 37 p refs
(Contract DAAG46-72-C-0165; DA Proj. 1W5-64603-D-385)
(AD-769937; AMMRC-CTR-73-30) Avail: NTIS CSCL 11/6

The response of the beta alloy TS6 (Ti; 10 Cr, 7 V, 3.5 Mo, 3 Al), to a wide variety of thermomechanical treatments has been investigated, including the effects of cold work on polygonized structures, the effects of cold-reduction temperature, and multi-stage aging. Combinations of strength and ductility can be manipulated within a wide range by varying the amount of cold work and the aging treatment. Mechanical properties are strongly dependent upon the mode of deformation during cold working and slight variations in alloy chemistry. Stress corrosion tests indicate superior performance of TS6 compared with similarly treated beta-120 VCA. A scale-up of ingot melting and processing techniques has been accomplished. Ingots of TS6 weighing twenty-eight pounds have been prepared using a master-alloy technique. Hot extrusion at 1800F has yielded two-inch diameter rod which has been successfully cold press-swaged 20% and cold rolled 90%. Compared with previous one-pound heats of TS6, this material overages earlier, at somewhat lower hardness levels, and with more rapid kinetics. (Modified author abstract) GRA

N74-17267# Frankford Arsenal, Philadelphia, Pa.
METALLURGICAL ADVANCES FOR ALUMINUM CARTRIDGE CASE APPLICATION
Henry P. George Jun. 1973 77 p refs
(DA Proj. 1W5-22604-A-010)
(AD-769861; FA-R-2081) Avail: NTIS CSCL 11/6

Previous ballistic tests indicated that the acceptance of a small arms, high-performance, aluminum alloy case required the development of aluminum alloy materials with strength and toughness combinations superior to those available in alloys commercially produced. Exploratory tests indicated that, when homogenized to contain less than 0.2 volume percent secondary phases, two new alloys (MA56 and MA61) which utilize high purity ingredients had a strength-toughness approaching that considered necessary. At a slightly lower strength level, alloy 7475 was found to have excellent toughness. A novel thermal mechanical treatment was employed to selectively harden the head. This cartridge case was used in conjunction with an invention (called a flexible internal element) to thwart accidental aluminum case burn-through and successfully demonstrated the flexibility of aluminum cases in high-performance small caliber ammunition. (Modified author abstract) GRA

N74-17271# Northrop Corp., Hawthorne, Calif. Aircraft Div.
CORRELATION OF PROPERTIES AND MICROSTRUCTURE IN WELDED TITANIUM ALLOYS Final Report, 15 Jun. 1972 - 15 Jun. 1973
K. C. Wu Sep. 1973 128 p refs
(Contract F33615-72-C-2015; AF Proj. 7351)
(AD-769919; NOR-73-110; AFML-TR-73-202) Avail: NTIS CSCL 11/6

The purpose of this program was to conduct a systematic investigation to correlate the metallurgical reactions during welding to the mechanical properties and microstructures in a Ti-6Al-6V-2Sn weldment. To study the fusion-zone microstructure resulting from various welding processes (cooling rates) and its mechanical properties, four welding processes, manual gas tungsten-arc welding, plasma arc welding, automatic gas tungsten-arc welding, and electron beam welding, were used. Thermal cycles in the heat-affected zone near the fusion line were measured for the four welding processes and the cooling rates from 2500F were interpolated or extrapolated. Thus, a correlation between welding processes, cooling rates, and the continuous-cooling transformation diagram was established and the relationships between the characteristics of welding processes and CCT diagrams could be identified. (Modified author abstract) GRA

N74-26462 Lockheed-California Co., Burbank.
THE LOCKHEED L-1011 TRISTAR FATIGUE AND FAIL-SAFE DEVELOPMENT PROGRAM
L. W. Nelson, M. A. Melcon, and H. Simons *In* RAE Fail-safe Aircraft Struct., Vol. 1 Mar. 1974 115 p refs

The various tests performed on the Lockheed L-1011 are described. The elements of the program included formulation of criteria, analysis, development tests, component design verification tests, and fatigue and fail-safe tests on two separate airframes.
Author (ESRO)

N74-27034# Battelle Columbus Labs., Ohio.
RESEARCH ON SYNTHESIS OF HIGH-STRENGTH ALUMINUM ALLOYS, PART 2 Annual Progress Report, 1 Jul. 1972 - 31 Jul. 1973
A. R. Rosenfield, C. W. Price, C. J. Martin, D. N. Williams, and D. C. Rennen Jul. 1973 135 p refs Prepared in cooperation with Reynolds Metals Co., Richmond
(Contract F33615-71-C-1805; AF Proj. 7353)
(AD-777159; AFML-TR-72-199-Pt-2; APR-2) Avail: NTIS CSCL 11/6

The program is divided into two tasks. The objective of Task A is to optimize the properties of aluminum alloys by controlling the concentrations and sizes of the small, intermediate, and large precipitates. Systematic variations in chemistry and also in the homogenization and aging treatments have provided a range of concentrations and sizes of the various precipitates in a series of alloys based on the 7075 and 2024 alloy compositions. Procedures for fracture toughness measurements of thin sheet material have been developed. Fatigue tests have also been conducted. The objective of Task B is to develop a recrystallized microstructure in wrought high-strength aluminum alloys during hot working. The desired microstructure is being

sought by control of hot-working conditions and also control of alloy composition. (Modified author abstract) GRA

N74-32001# Dayton Univ. Research Inst., Ohio.
MECHANICAL PROPERTIES OF Ti-6Al-4V ANNEALED FORGINGS Final Report, Jun. 1971 - Oct. 1973
Russell R. Cervay Mar. 1974 32 p refs
(Contract F33615-72-C-1282; AF Proj. 7381)
(AD-779937; UDRI-TR-73-16; AFML-TR-74-49) Avail: NTIS CSCL 11/6

Tests were conducted to determine the mechanical properties of titanium 6Al-4V annealed forgings. Tensile, fracture toughness, and constant amplitude cyclic crack growth properties were obtained along with limited corrosion studies of fastener installations. The tensile properties were determined for three orientations and the fracture toughness properties for four orientations. Some of the tensile and fracture toughness specimens were subjected to a time-temperature exposure before being tested at room temperature. The mechanical properties of the annealed material were similar to those in the literature. The time-temperature exposure cycle slightly altered the mechanical properties of the material. The corrosion tests conducted on the fastener installations did not produce any cracking in the material under the test conditions. Author (GRA)

N75-10506# Battelle Columbus Labs., Ohio.
THE COLLECTION, GENERATION, AND ANALYSIS OF MIL-HDBK-5 ALLOWABLE DESIGN DATA Annual Report, 15 Feb. 1973 - 15 Feb. 1974
Paul E. Ruff and Walter S. Hyler May 1974 66 p refs
(Contract F33615-73-C-5053)
(AD-783616; AFML-TR-74-67) Avail: NTIS CSCL 11/6

The annual report describes highlights of the activities, and progress of the MIL-HDBK-5 program from February 15, 1973, through February 15, 1974. The Military Standardization Handbook, MIL-HDBK-5B, Metallic Materials and Elements for Aerospace Vehicle Structures, is recognized as the primary source for design allowable data by the Department of Defense (DoD) and other Government agencies responsible for aerospace vehicle design. The Handbook contains design allowable data on metallic materials, fasteners, joints, and other structural elements. A fatigue data consolidation and statistical analysis procedure was developed. The method of analysis was tested on collections of fatigue data for 2024 and 7075 aluminum alloys, Ti-6Al-4V alloy, and 300M steel with generally good results. Topics studied include fracture toughness stress corrosion and stress strain relations. GRA

N75-24930# Air Force Systems Command, Wright-Patterson AFB, Ohio. Foreign Technology Div.
STUDY OF THE PROTECTION OF THE TITANIUM BOLT ASSEMBLY
G. Sertour and M. Guerlet 20 Mar. 1975 50 p Transl. into ENGLISH "Emis Par le Serv. Technique Aeron., Section Materlaux 22" France, 22 Nov. 1973 p 1-41
(AD-A007945; FTD-HC-23-0975-75) Avail: NTIS CSCL 13/5

The finishing presently used on the T-A6V bolt assembly--anodic sulfuric oxidation, lubrication with molybdenum bisulfate, is inconvenient in certain respects; in particular, from the point of view of corrosion of the poles by galvanic couples and adhesion of paints and mastics on the screw heads. The tests consisted of comparing various possible methods of protection, encountered during tests defined according to various norms. Among the tested protective agents, MoS2, Cadmium and Aluminum, only the aluminum protection agent gave results which were satisfactory in all respects. GRA

N75-24931# RMI Co., Niles, Ohio. Research and Development Dept.
GRAIN REFINEMENT OF TITANIUM ALLOYS Final Technical Report, May 1973 - Jun. 1974
M. J. Buczek, G. S. Hall, S. R. Seagle, and H. B. Bomberger Nov. 1974 142 p refs
(Contract F33615-73-C-5106; AF Proj. 7351)
(AD-A008532; AFML-TR-74-255) Avail: NTIS CSCL 11/6

The objective of this program was to determine the optimum amounts of yttrium added either as the oxide or element for grain refinement to commercial Ti-6Al-4V and Ti-38-6-44 titanium alloys and establish the effects on subsequent mechanical behavior and sonic inspectability. The properties of cast 8-inch-diameter ingots as well as 3-inch bar processed from these ingots were evaluated at yttrium contents up to 0.1 percent. Nearly all the mechanical property data were obtained on alloys containing 0.03 percent yttrium. At this level, significant grain refinement was not observed in Ti-38-6-44 although improved sonic inspectability. Higher transverse ductility and improved stress-corrosion resistance were observed. At the same 0.03 percent yttrium content, the recrystallized Ti-6Al-4V beta grain size was reduced and improved sonic inspectability and ductility were obtained in wrought and cast products. GRA

N75-27155# Naval Ship Research and Development Center, Annapolis, Md.
STRESS RELIEF HEAT TREATMENT OF MANGANESE-NICKEL-ALUMINUM BRONZE AND MANGANESE-BRONZE WELDMENTS
Charles A. Zanis Jan. 1975 26 p refs
(AD-A004578; NSRDC-4447) Avail: NTIS CSCL 11/6

Tensile properties, weldability, general corrosion, and corrosion-fatigue properties were determined as a function of stress-relief heat treatment for both cast Mn-Ni-Al bronze and manganese-bronze propeller alloys. It was found that Mn-Ni-Al bronze is susceptible to stress-corrosion cracking in the as-welded heat-affected zone. Stress-relief heat treatments in the range of 700 to 1200F were effective in eliminating the stress-corrosion cracking in this alloy. Manganese-bronze weldments exhibited poor weldability but were not found susceptible to stress-corrosion cracking. High-cycle corrosion-fatigue tests on weldments revealed an endurance strength at 10 to the 8th power cycles of 12,000 pounds per square inch for Mn-Ni-Al bronze and 7,500 to 11,000 pounds per square inch for manganese bronze. GRA

N75-30303# Army Foreign Science and Technology Center, Charlottesville, Va.
HIGH STRENGTH, HEAT RESISTANT AND STRUCTURAL ALLOYS OF ALUMINUM WITH LITHIUM
M. B. Altman 18 Sep. 1974 40 p refs Transl. into ENGLISH from Alyuminievye Splavy (USSR), no. 7, 1972 p 204-230
(AD-A005977; FSTC-HT-23-0911-74) Avail: NTIS CSCL 11/6

This is chapter 7 of a book entitled Aluminum Alloys, Industrial, Deformable, Sintered and Cast Aluminum Alloys. These alloys are broken down into groups depending on their properties, use and chemical composition. This chapter deals with aluminum alloys alloyed with lithium, with lithium and cadmium, and with lithium and magnesium. Research on proportions, alloying procedures, and the resulting properties of alloys (VAD23 and 01420 alloys in particular) are discussed in detail. Data on mechanical properties at various temperatures and physical and corrosion properties of the alloys are included. GRA

N76-12136# Air Force Rocket Propulsion Lab., Edwards AFB, Calif.
PRELIMINARY FLIGHT RATING TESTS OF THE HAST PROPULSION SYSTEM Final Report
Carlton D. Penn and John E. Branigan Jan. 1975 199 p refs
(AF Proj. 3148)
(AD-A012200; AFRPL-TR-75-5) Avail: NTIS CSCL 21/8

Preliminary Flight Rating Tests of the hybrid rocket propulsion system for the HAST target missile were accomplished by the Air Force Rocket Propulsion Laboratory. Nine tests of the flight configuration system were conducted at simulated altitude. Overall operating characteristics and performance were shown to be satisfactory for missile flight tests. GRA

N76-18271# Lockheed Missiles and Space Co., Palo Alto, Calif. Research Lab.
CORRELATION OF MICROSTRUCTURE WITH FRACTURE TOUGHNESS PROPERTIES IN METALS, PART 2 Final Report, 21 Nov. 1973 - 21 Jan. 1975
Richard E. Lewis and Frank A. Crossley 21 Jan. 1975 67 p refs
(Contract N00019-74-C-0161)
(AD-A015977; LMSC-D454884-Pt-2) Avail: NTIS CSCL 11/6

Ti-6Al-4V alloy in three mill product forms and Ti-6Al-6V-2Sn-0.7Fe-0.7Cu (Ti-662) alloy in one product form were studied for the purpose of establishing a correlation between microstructures and fracture toughness. The Ti-6Al-4V mill products were 1- and 2.4-in. plates and 4- x 4-in. forged billets. The Ti-662 product was 1-in. plate. Alloy, mill produce, processing and heat-treatment variables produced 21 microstructural conditions, complementing the 28 conditions studied in a previous contract with Naval Air Systems Command, Contract N00019-72-C-0545. Tension test, fracture toughness, salt-water stress-corrosion crack-growth threshold, and fatigue crack growth rate properties

A73-25514 # **X2048, a high strength, high toughness alloy for aircraft applications.** S. A. Levy, R. E. Zinkham, and G. E. Spangler (Reynolds Metals Co., Richmond, Va.). *AIAA, ASME, and SAE, Structures, Structural Dynamics, and Materials Conference, 14th, Williamsburg, Va., Mar. 20-22, 1973, AIAA Paper 73-385.* 7 p. Members, $1.50; nonmembers, $2.00.

X2048 is an alloy which retains all of the desirable properties of 2024 or 2124-T851, but exhibits fracture toughness equal to/or greater than 2219-T851. Testing of three inch thick plant-produced plate has shown that the strength corrosion resistance, fatigue resistance, and elevated temperature stability of 2X24-T851 are maintained. Through control of chemistry and processing, the level of brittle second phase particles is substantially reduced for the new alloy. Short transverse elongations as high as 8% have been obtained for X2048. (Author)

A75-17575 **Alloys for spars of rotor blades of helicopters.** E. I. Kutaitseva, V. S. Komissarova, I. V. Butusova, and N. V. Egorova. *(Metallovedenie i Termicheskaia Obrabotka Metallov,* no. 5, 1974, p. 15-18.) *Metal Science and Heat Treatment,* vol. 16, no. 5-6, Nov. 1974, p. 381-383. Translation.

The AVT1 and AD33T1 alloys of the Al-Mg-Si system currently used in hollow spars of helicopter rotor blades, and a new V91T1 alloy of the Al-Zn-Mg-Cu system were studied by electron microscopy and in fatigue tests in air and in a 0.001% NaCl solution. The V91T1 alloys were found to exhibit the best fatigue and corrosion strength. The test data are tabulated and electron microphotographs are presented. V.P.

A75-20449 # **Type IV class 1 & 2 commercial airplane hydraulic fluids.** W. G. Nelson and A. W. Waterman (Boeing Commercial Airplane Co., Seattle, Wash.). *Sperry Rand Corp., Aerospace Fluid Power Conference, 23rd, Troy, Mich., Nov. 18, 19, 1974, Paper.* 52 p.

During 1973-1974 Boeing has worked with the three suppliers of aircraft phosphate ester hydraulic fluids to develop and qualify Type IV low-density fluids in specific response to erosion resistance in the presence of chemical contaminants. Two such fluids have been approved for airline use. These fluids have been shown to tolerate 1000 ppm of an in-service chemical contaminant, arrest erosion when used as a 50/50 mixture with a contaminated fluid, and provide improved thermal stability by passing more stringent specification test requirements. Future developments are progressing on schedule for the development and qualification of high-density candidate fluids in response to customer interest. The objective of improving valve hardware for tolerance to erosion is being addressed by conducting evaluations of advanced port configurations. (Author)

A75-20990 **New high strength aluminium alloy.** H. A. Holl (Ministry of Defence /Procurement Executive/, London, England). *Aircraft Engineering,* vol. 47, Jan. 1975, p. 25-32. 9 refs. Research supported by the Ministry of Defence (Procurement Executive).

Information is presented on the properties and the potential applications of a new aluminum-zinc-magnesium-copper alloy. The properties of the new alloy are compared with the properties of aluminum alloys currently used for airframe construction. Questions of alloy composition, heat treatment, and metallurgical characteristics are considered. Attention is given to tensile properties, stress-corrosion resistance, exfoliation corrosion resistance, fracture toughness, fatigue strength and crack propagation resistance, and properties of product forms other than plate. G.R.

N75-74424 Lockheed-Georgia Co., Marietta. Advanced Structures Div.
MATERIALS GOALS FOR IMPROVED STRUCTURAL ALLOYS Final Summary Report, May 1969 - Jul. 1970
George W. Stacher Sep. 1970 167 p
(Contract F33615-69-C-1642; AF Proj. 7351)
(AD-A001085; AFML-TR-70-225)

A compilation of data involving use of materials on selected aircraft areas of two types of aircraft has been accomplished. Wing surface, wing internal section, fuselage panel and landing gear data concerning the use of aluminum, steel and titanium have been compiled for a large cargo aircraft (C-5) and a supersonic fighter. Data Consists of mechanical property items, corrosions, producibility, maintainability, availability and cost pertaining to the above sections and material. Direct comparison of the materials in conjunction with the study parameters in each application has been made for the two aircraft and presented. Also included is the effect of selected mechanical property improvements on the weight of aircraft structure. By assuming certain percentages of improvements in the property levels of the three materials considered, computerized data was collected indicating the effect of the improvements on weight of each of the three sections evaluated. Appropriate curves have been generated indicating those material areas warranting development.

N75-77680 Naval Ship Research and Development Center, Annapolis, Md.
PROPERTIES OF MODIFIED NITINOL ALLOYS Research and Development Report
J. P. Gudas, D. A. Davis, and F. J. Gomba Mar. 1973 28 p
(Proj. ZR000-0101)
(AD-781469; NSRDC-3919; NSRDC-28-503)

This investigation deals with the production and testing of 11 modified nitinol alloys. Corrosion properties, mechanical properties, processing parameters, and microstructural characteristics have been determined as the function of alloy type. Results indicate that substitutional additions of Mo, Fe, and Cr are beneficial in preventing localized crevice corrosion. Further studies are being undertaken to determine long-term corrosion behavior of alloys produced as well as to broaden the data base describing the effects of the level of alloy content.
Modified Author Abstract

N75-77844 Aluminum Co. of America, Alcoa Center, Pa. Physical Metallurgy Div.
DEVELOPMENT OF AN Al-Mg-Li ALLOY Final Technical Report, 8 Feb. 1973 - 8 Feb. 1974
Joseph W. Evancho Jun. 1974 186 p
(Contract N62269-73-C-0219)
(AD-787027)

Four Al-Mg-Li alloys were investigated for potential use in high performance aircraft. Ingot casting was very difficult. Fabricating was also difficult; however, a limited amount of sheet and some upset forgings were fabricated. Solution heat treatment practices providing highest strenghth were determined and aging surveys for each alloy were conducted. Cold working between solution heat treatment and artificial aging significantly affected response to artificial aging. Elastic moduli were higher and densities were lower than those of other aluminum alloys. Elevated temperature strengths were comparable to those of 2020-T6. Resistance to exfoliation corrosion was comparable to 7075-T76 sheet, but the alloys were highly susceptible to stress-corrosion cracking. Toughness of these alloys was also very low. Modified Author Abstract

N75-78044 United Aircraft Research Labs., East Hartford, Conn.
DEVELOP, FABRICATE AND TEST HIGH STRENGTH DIRECTIONALLY SOLIDIFIED EUTECTIC ALLOYS Final Report, Mar. - Dec. 1973
Edwin H. Kraft, Earl R. Thompson, and Valentino M. Patarini Apr. 1974 80 p
(Contract N62269-73-C-0310)
(AD-778655; UARL-N911649-3)

A directionally solidified eutectic alloy was synthesized based on the Ni-Cr eutectic, but containing in addition to nickel, 37.0 w/o Cr, 18.0 w/o W, 10.0 w/o Co and 0.1 w/o Al. This eutectic, while not of optimized composition, shows superior oxidation-hot corrosion resistance over existing eutectic alloys and some nickel base superalloys, and as a system holds promise of a strength advantage over the superalloys in the temperature

region of 2,000 F and above. Use of the Ni3Cb reinforced eutectics has been made more practical by demonstration of superplastic bonding of a superalloy to the gamma prime-delta (Ni-23.1Cb-4.4Al) eutectic, such as would be done in forming a turbine blade root. The effect of particle impingement on this eutectic and the gamma-gamma prime-delta (Ni-20.7Cb-3.Al) eutectic was studied and showed that while some cracking can be expected with high impact energies, microstructural changes are limited to the immediate area of the impact. Heat treatment was shown to increase the room temperature and intermediate temperature strength of both delta reinforced eutectics, but has little effect at 2,000 F. Author

76-13001 Naval Intelligence Support Center, Washington, D.C. Translation Div.

STRUCTURAL MATERIALS FOR FABRICATION OF SHIP REACTORS AND STEAM GENERATORS

P. A. Manko and B. E. Soloimskii Feb. 1973 114 p Transl. into ENGLISH from Mono. Kostruktivnye Mater. Dlya Izgstovleniya sudovykh reaktorov parogeneratorov, n. p., 1969 p 31-5108, 167-179, 187-195, 208-210
(AD-757725; NISC-Trans-3385)

Contents: structural materials for nuclear reactors and steam generators; technology of fabrication of basic parts and subassemblies of reactors and boilers; quality control of reactor and steam generator parts and assemblies by means of ultrasonic flaw detection; and assembly of reactors and steam boilers on board ships.

76-13002 Battelle Columbus Labs., Ohio. Metals and Ceramics Information Center.

TITANIUM ALLOYS HANDBOOK

Richard A. Wood and Ronald J. Favor Dec. 1972 644 p
(Contract DSA900-73-C-0922)
(AD-758335; MCIC-HB-02)

This handbook represents the third edition of an earlier document. The first and second both entitled 'Aircraft Designer's Handbook on Titanium and Titanium Alloys' were published in August 1965 and March 1967, respectively. Information presented in the handbook was obtained from many sources. Those cooperating included government agencies, the titanium producers, airframe and engine companies, and many others. The practice of referencing these various sources has been followed in all sections of the handbook. The information is representative of good engineering practice even though actual designs and fabrication processes may vary from those recommended in other sources. Metallurgy, availability, machining and forming, joining, and mechanical properties of titanium alloys are presented.

76-13003 Battelle Columbus Labs., Ohio.

TITANIUM CASTINGS TODAY

J. G. Kura Dec. 1973 118 p
(Contract DSA900-74-C-0616)
(AD-772725; MCIC-73-16) Avail: Non-U.S. Addressees HC $18.50/MF $18.50

Titanium castings weighing from a few grams to over half a ton are being produced. Three foundries produce castings in rammed graphite molds chiefly for applications where high resistance to corrosion is important. Three other foundries use investment molds exclusively to produce precision castings, chiefly for the aerospace industry. Maximum pour weight is about 350 pounds. Investment castings are almost free of surface contamination while rammed-mold castings have a contaminated skin that does not affect the corrosion resistance of the castings. The contaminated skin can be completely removed by chemical milling. Casting design guides and inspection standards are similar to those used for steel castings or superalloy castings. Defects encountered are similar to those common to other castings. Weld repairing of defects is practiced and, when properly done, has no adverse effect on the properties of the castings. Radiographic standards are being developed specifically for titanium castings. One rammed-mold foundry uses a water-soluble core which allows the production of cored cavities of complex shapes. Several grades of castings are produced in unalloyed titanium and in the Ti-6Al-4V alloy. In general, the mechanical properties of titanium castings compare favorably with those for forgings. Author

76-13004 Battelle Columbus Labs., Ohio. Metals and Ceramic Information Center.

PROPERTIES OF TEXTURED TITANIUM ALLOYS

Frank Larson and Anthone Zarkades Jun. 1974 83 p
(Contract DSA900-74-C-0616)
(AD-781884; MCIC-74-20)

This report reveals that many important engineering properties of titanium and its alloys are anisotropic and that this anisotropy can be used to achieve improvements in structures and other applications. From this review of textures found in commercial titanium products and the way in which they develop, it can be seen that a wide variety of different types are possible and many others will undoubtedly be developed as the knowledge increases or a specific need arises.

76-13005 Army Foreign Science and Technology Center, Charlottesville, Va.

A NEW CONSTRUCTION MATERIAL: TITANIUM

I. I. Kornilov, N. M. Fedorchuk, and V. M. Berenblum Jan. 1974 25 p Transl. into ENGLISH from Mono. Movyi Konstrukt. Material (Moscow), 1972 p 6-15, 131-134, 193-197
(AD-A002645; FSTC-HT-23-246-74)

The book from which these excerpts are taken presents new research on the chemical interaction of titanium with various elements, and looks at phase transformation in certain alloy systems. The articles give the results of studying the electrochemical behavior of titanium and its alloys in aggressive media, and also the oxidizability of the most important titanium alloys.

76-13006 Frankford Arsenal, Philadelphia, Pa.

THERMOMECHANICAL TREATMENTS ON HIGH STRENGTH Al-Zn-Mg(-Cu) ALLOYS

E. DiRusso, M. Conserva, F. Gatto, and H. Markus Jun. 1972 15 p Pub. in Met. Trans., v. 4, Apr. 1973 p 1133-1144
(DA Proj. 1-T-162105-AH-84)
(AD-A003295; FA-TA-74037)

An investigation was carried out to determine the metallurgical properties of Al-Zn-Mg and Al-Zn-Mg-Cu alloy products processed according to newly developed final thermomechanical treatments (FTMT) of T-AHA type. The results show that these cycles can be utilized to produce wrought products of high purity Al-Zn-Mg(-Cu) alloys characterized by equivalent toughness and ductility and much higher strength than conventionally processed commercial purity materials. Based on transmission electron microscopy studies, it was found that such improved behavior of FTMT material is attributable to the superposition of hardening effects, from aging precipitation and from dislocations. Preliminary stress-corrosion and fatigue tests indicate that these indicate that these properties are not substantially influenced by T-AHA thermomechanical process. Further work is needed in this area, in order to better understand the directions to follow for developing better alloys. Author

76-13007 Battelle Columbus Labs., Ohio.

ENGINEERING DATA ON NEW AEROSPACE STRUCTURAL MATERIALS Final Summary Report, Apr. 1973 - Apr. 1975

Omar L. Deel, Paul E. Ruff, and H. Mindlin Jun. 1975 287 p
(Contract F33615-73-C-5073; AF Proj. 7381)
(AD-A017848; AFML-TR-75-97)

The major objectives of this research program were to evaluate newly developed materials of interest to the Air Force for potential structural airframe usage, and to provide data sheet type presentations of engineering data for these materials. The effort covered in this report has concentrated on 7049-T7351 plate, Inconel 617 annealed sheet, 7475-T7351 plate, 2419-T851 plate, Ti-6Al-2Zr-2Sn-2Mo-2Cr duplex-annealed forging, Ti-6Al-2Cb-1Ta-1Mo annealed plate, Ti-6Al-4V beta-annealed plate, Ti-6Al-4V annealed castings, Ti-6Al-4V isothermal forgings, Incoloy 903 heat-treated sheet, and 201.0 T7 castings. The properties investigated include tension, compression, shear, bend, impact, fracture toughness, fatigue, creep and stress-rupture, and stress corrosion at selected temperatures.

76-13008 Dayton Univ. Research Inst., Ohio.

MECHANICAL PROPERTY DATA FOR ALUMINUM ALLOY 2419-T851 PLATE Final Report, May 1974 - Jun. 1975

John J. Ruschau Sep. 1975 31 p

(Contract F33615-74-C-5024; AF Proj. 7381)
(AD-A018159; AFML-TR-75-136)

Tensile, fracture toughness, fatigue, fatigue crack growth, and stress corrosion properties for aluminum alloy/temper 2419-T851 two-inch-thick-plate were determined. The material was obtained from the Aluminum Company of America (ALCOA). Material property comparisons were then drawn between data developed from a single plate of the test alloy and aluminum alloy 2219 plate in the T851 heat treatment condition.

76-13009 Aerojet Liquid Rocket Co., Sacramento, Calif.
STORABILITY INVESTIGATIONS OF WATER, LONG TERM STORAGE EVALUATION Annual Report, 15 Aug. 1974 - 30 Sep. 1975
E. M. VanderWall and G. R. Janser Dec. 1975 65 p
(Contract F04611-72-C-0062; AF Proj. 3059)
(AD-A019279; AFRPL-TR-75-62)

The objective of this program is to gather data that will permit the Air Force to assess the long term storage characteristics of water particularly with regard to formation of particulate matter, so that the feasibility of long-term storage of water for use as a transpiration coolant can be determined. Five metallic materials of construction are included in this program: 304 stainless steel, A-286 (aged) steel, 17-4 (aged) stainless steel, Inconel 718 (aged), 6Al-4V titanium (STA). Two types of water are used in the program; oxygen-saturated, deionized, filtered, and oxygen-free, deionized, filtered. Five-year storage tests have been initiated in 304 and 17-4 PH stainless steels, A-286 steel, Inconel 718, and 6-Al-4V titanium (STA) containers using the filtered, deionized waters. Evaluation of water and containers stored for eighteen months and twenty-four months has been completed. The data show that both oxygen-saturated and oxygen-free water can be stored in appropriate metal containers for the selected time periods without detrimental particulate matter formation or significant changes in the quality of the water.

76-13010 Pratt and Whitney Aircraft, West Palm Beach, Fla. Research and Development Center.
BERYLLIUM/TITANIUM BIMETAL SYSTEM Final Report, 10 Sep. 1973 - 5 Jun. 1975
Arthur R. Cox Sep. 1975 33 p
(Contract N00019-74-C-0117)
(AD-A019657; PWA-FR-7273)

The purpose of this program was to determine the engineering value of a powder metal beryllium/titanium material as applied to the F401 gas turbine engine. Two material types, one 50 percent beryllium by volume and the second 60 percent beryllium by volume, were selected for evaluation with respect to augmentor nozzle actuation links. Mechanical, metallurgical, and corrosion resistant tests were run for each material and parts designed and fabricated on the basis of these results. The fabricated link assemblies were tested against part operating criteria and the results showed that both materials buckling at 600 F. Also, in cyclic tests to determine component durability both materials were satisfactory. An attachment failure caused one of the two link configurations to fail permaturely; however, subsequent analysis showed this was correctable by a simple design and modification. Author

76-13011 National Aerospace Lab., Amsterdam (Netherlands). Struct. Mater. Div.
FRACTURE MECHANICS APPROACH TO THE USE OF TITANIUM ALLOYS FOR THICKER-SECTION AIRFRAME COMPONENTS
R. J. H. Wanhill [1973] 13 p J. Inst. Metals, Coden: JIMEAP, Publ: 73, Series: 101, Oct. p 258-270 Section: CA056007; Publ. Class: J; Coverage: 11
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14. Abstract

The true annual cost of corrosion in NATO aircraft is appallingly large, in spite of the advanced state of knowledge in this field. Interruption and reduction of service, failure of mission, hazards to personnel because of operating failures are additional important factors when assessing corrosion impact. Yet, most premature corrosion damage and failures occur for reasons already well-known, and to a major degree could be prevented by proper and timely appreciation of the problem and threat, and by the use of known preventive methods. Clearly, greater visibility of the problems, expanded engineering education and better practical transfer of technology and knowledge are needed. This Lecture Series was structured with this situation in mind. It covers the significance, implications and economics of corrosions, and the threats and preventive measures for the product life cycle: design, material selection, construction, maintenance and repair, inspection and test.

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